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Wenatchee River Temperature Total Maximum Daily Load Study

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Wenatchee River Temperature Total Maximum Daily Load Study

by

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Washington State Department of Ecology
Environmental Assessment Program

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Abstract

The Wenatchee River and some of its tributaries – Chiwaukum Creek, Icicle Creek, Little Wenatchee River, Nason Creek, Mission Creek, and Peshastin Creek – are included in the 1998 303(d) list for impaired waters for temperature in Washington State.

As part of the Wenatchee River Total Maximum Daily Load (TMDL) study for temperature, the Washington State Department of Ecology conducted field work during 2002-2003. This report presents an analysis of the stream water spatial and temporal temperature patterns of selected streams in the Wenatchee River basin based on instream data and thermal infrared radiation (TIR) surveys from 2002 and 2003. A stream temperature model, QUAL2Kw, was used to investigate possible thermal behaviors of the streams for different meteorological, shade, and flow conditions.

Reductions in water temperature are predicted for hypothetical conditions with mature riparian vegetation and improvements in riparian microclimate. Model simulations performed at 7-day average with 10-year return (7Q10) period flow conditions show that an average reduction of 2.7°C is expected compared with the current conditions. Potential reduced temperatures are predicted to be less than the threshold for fish lethality of 23°C, but greater than 18°C in Class A and greater than 16°C in Class AA waters in some or most of the segments in all streams that were evaluated.

This technical assessment uses effective shade as a surrogate measure of heat flux to fulfill the requirements of the federal Clean Water Act Section 303(d) for a temperature TMDL. Effective shade is defined as the fraction of incoming solar shortwave radiation that is blocked by vegetation and topography from reaching the surface of the stream.

In addition to load allocations for effective shade, other management activities are recommended for compliance with the water quality standards for water temperature.

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- Dave Schneider for review of the draft report and coordination of the public review process.
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- Dustin Bilhimer for extensive field work and analysis of environmental data.
- Joan LeTourneau for formatting and editing the final report.

Introduction

The Washington State Department of Ecology (Ecology) is required by the federal Clean Water Act to conduct a Total Maximum Daily Load (TMDL) evaluation for all waterbodies on the 303(d) list. The evaluation process includes a water quality technical study to determine the capacity of the waterbody to absorb pollutants and still meet water quality standards. The study also evaluates the likely sources of those pollutants, and the specific amount of pollution (the pollutant load) that needs to be reduced to meet state water quality standards. During and after the technical study, Ecology works with other agencies and local citizens to identify pollution controls based on the study findings. A TMDL study for the Wenatchee River watershed was begun in 2002 and is summarized in this report.

The Wenatchee River watershed is located in Chelan County. A map of the study area is shown in Figure 1. The technical study to address water quality concerns in the Wenatchee River watershed, also known as Water Resources Inventory Area number 45 (WRIA 45), was split into two years of field data collection. The first study year, with field data collection during 2002, was focused on the mainstem Wenatchee River from the outlet of Lake Wenatchee to the river's confluence with the Columbia River at the city of Wenatchee, and includes Icicle Creek. The second study year, with data collection during 2003, was focused on the other major tributaries to the Wenatchee River.

The 1998 303(d) list for temperature in the Wenatchee River watershed is presented in Table 1. Ecology is in the process of updating the list of impaired waters for the state of Washington. Following guidance from the U.S. Environmental Protection Agency (EPA), the 2002/2004 listing process includes a much more comprehensive assessment of Washington's waters than previous 303(d) lists. The 2004 303(d) list is a work in progress, and revisions can be found on Ecology's Web page (www.ecy.wa.gov/programs/wq/303d/2002/2002-index.html).

Table 1. 1998 303(d) listings for temperature in the Wenatchee River watershed.

<table>
<tr><th>Waterbody</th><th>Township</th><th>Range</th><th>Section</th><th>IIP 303(d) number</th><th>WBID number</th></tr>
<tr><td>Chiwaukum Creek</td><td>25N</td><td>17E</td><td>09</td><td>HM20EV56.298</td><td>WA-45-1900</td></tr>
<tr><td>Icicle Creek</td><td>24N</td><td>17E</td><td>30</td><td>KN36FW12.147</td><td>WA-45-1017</td></tr>
<tr><td>Little Wenatchee River</td><td>27N</td><td>16E</td><td>15</td><td>DS66LF1.842</td><td>WA-45-4000</td></tr>
<tr><td>Mission Creek</td><td>23N</td><td>19E</td><td>20</td><td>DQ04NW5.629</td><td>WA-45-1012</td></tr>
<tr><td rowspan="2">Nason Creek</td><td>26N</td><td rowspan="2">17E</td><td>09</td><td>FZ91ME0.000</td><td rowspan="2">WA-45-3000</td></tr>
<tr><td>27N</td><td>27</td><td>UO87HL0.288</td></tr>
<tr><td rowspan="2">Peshastin Creek</td><td rowspan="2">24N</td><td rowspan="2">18E</td><td>21</td><td>OM13EX0.638</td><td>WA-45-1014</td></tr>
<tr><td>32</td><td>OM13EX4.357</td><td>WA-45-1013</td></tr>
<tr><td>Wenatchee River</td><td>23N</td><td>20E</td><td>28</td><td>HM20EV0.600</td><td>WA-45-1010</td></tr>
</table>

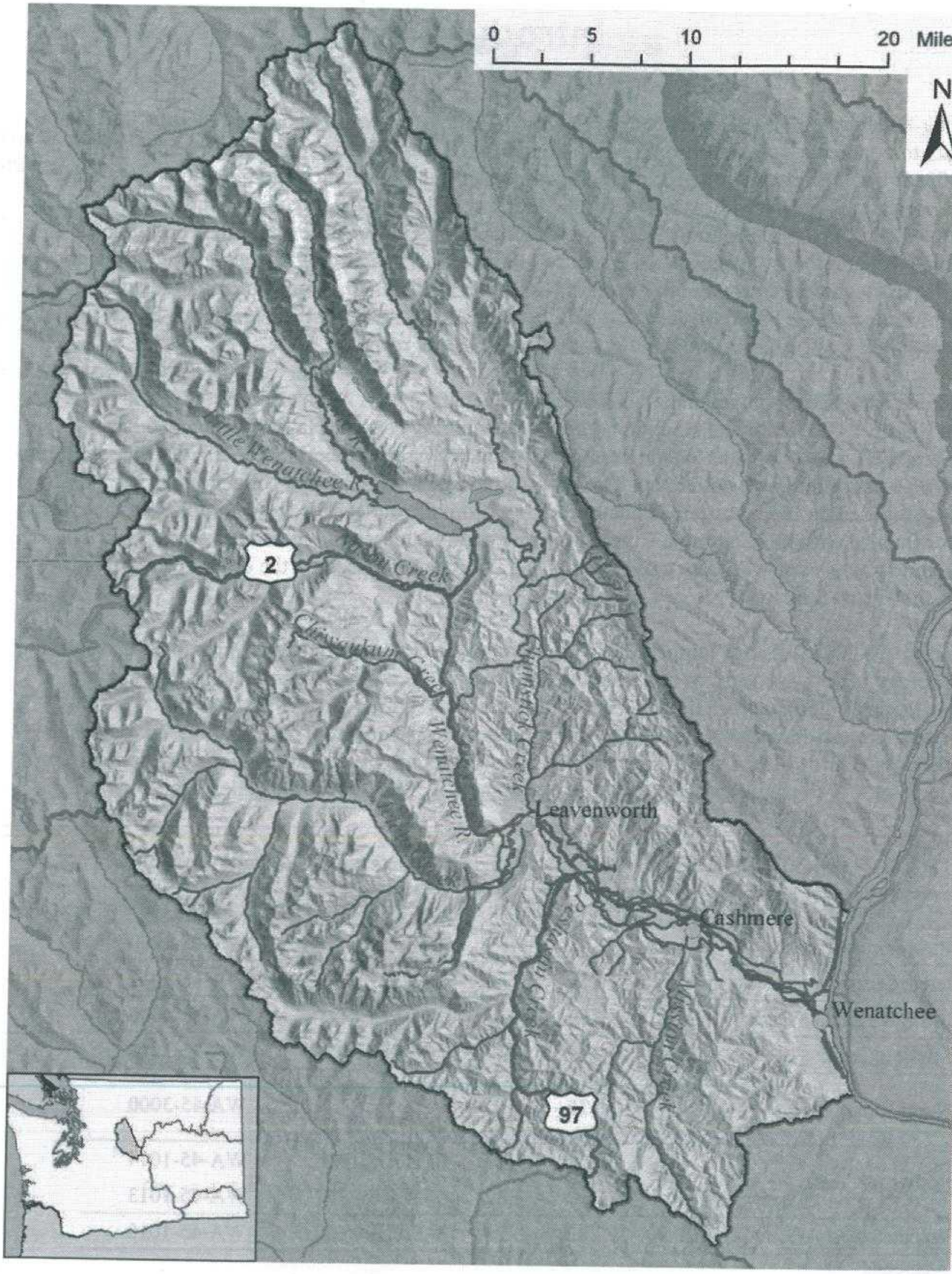


Figure 1. Study area map for the Wenatchee River Temperature TMDL.

Overview of stream heating processes

The temperature of a stream reflects the amount of heat energy in the water. Changes in water temperature within a particular segment of a stream are induced by the balance of heat exchange between the water and the surrounding environment during transport through the segment. If there is more heat energy entering the water in a stream segment than there is leaving, then the temperature will increase. If there is less heat energy entering the water in a stream segment than leaving, the temperature will decrease. The general relationships between stream parameters, thermodynamic processes (heat and mass transfer), and stream temperature change are outlined in Figure 2.

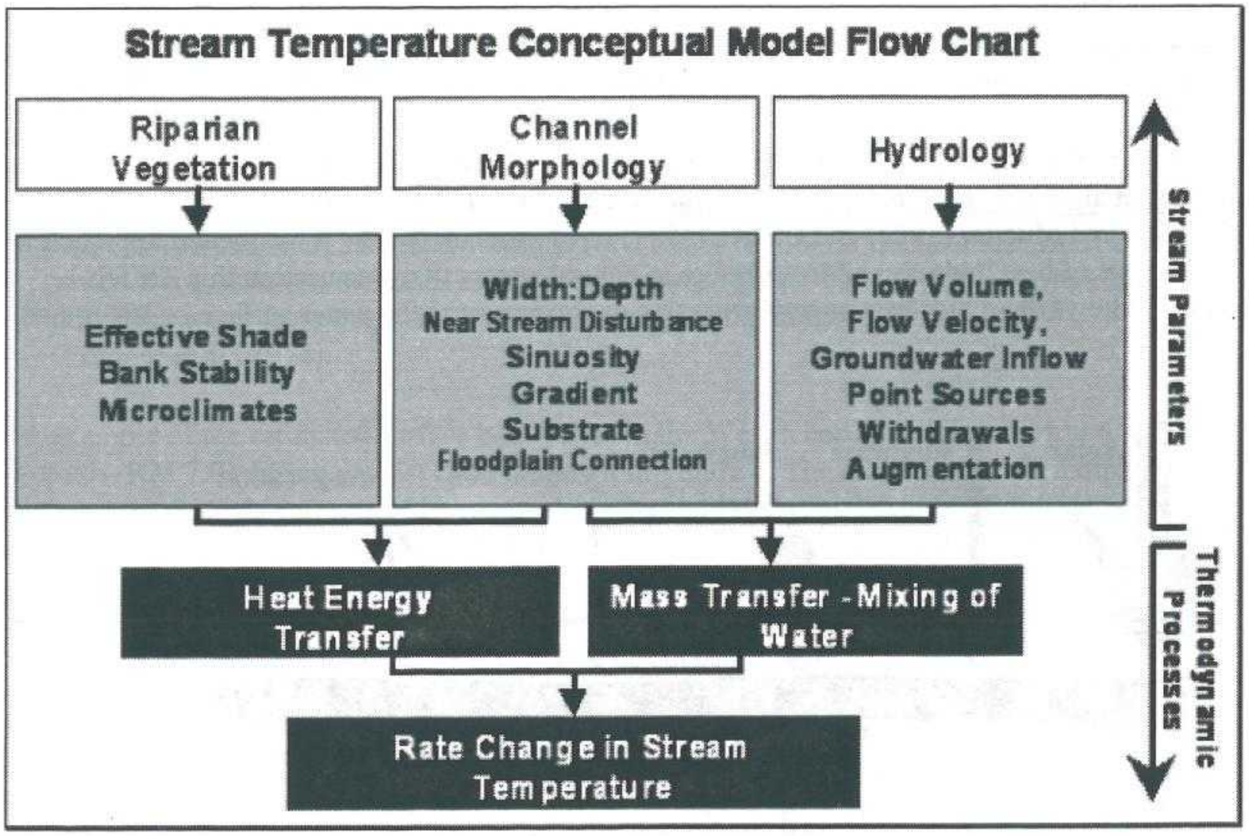


Figure 2. Conceptual model of factors that affect stream temperature.

Adams and Sullivan (1989) reported that the following environmental variables were the most important drivers of water temperature in forested streams:

- **Stream depth.** Stream depth is the most important variable of stream size for evaluating energy transfer. Stream depth affects both the magnitude of the stream temperature fluctuations and the response time of the stream to changes in environmental conditions.
- **Solar radiation and riparian vegetation.** The daily maximum temperatures in a stream are strongly influenced by removal of riparian vegetation because of diurnal patterns of solar heat flux. Daily average temperatures are less affected by removal of riparian vegetation.
- **Groundwater.** Inflows of groundwater can have an important cooling effect on stream temperature. This effect will depend on the rate of groundwater inflow relative to the flow in the stream and the difference in temperatures between the groundwater and the stream.

Heat budgets and temperature prediction

The transport and fate of heat in natural waters has been the subject of extensive study. Edinger et al. (1974) provide an excellent and comprehensive report of this research. Thomann and Mueller (1987) and Chapra (1997) have summarized the fundamental approach to the analysis of heat budgets and temperature in natural waters that was used in this TMDL. Figure 3 shows the major heat energy processes or fluxes across the water surface or streambed.

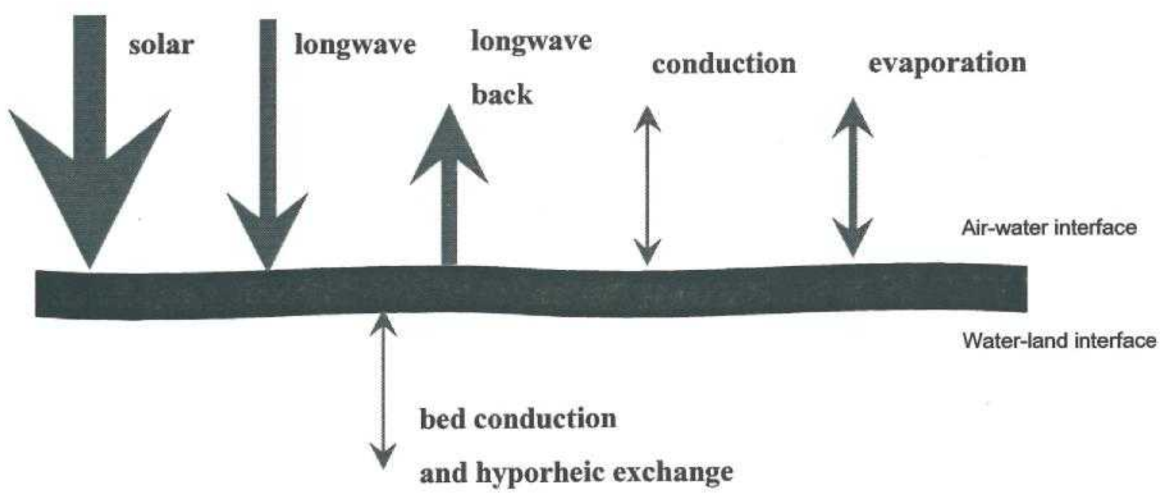


Figure 3. Surface heat exchange processes that affect water temperature (net heat flux = solar + longwave atmosphere + longwave back + convection + evaporation + bed). Heat flux between the water and streambed occurs through conduction and hyporheic exchange.

The heat exchange processes with the greatest magnitude are as follows (Edinger et al., 1974):

- **Shortwave solar radiation**. Shortwave solar radiation is the radiant energy which passes directly from the sun to the earth. Shortwave solar radiation is contained in a wavelength range between 0.14 μm and about 4 μm. At Washington State University's (WSU) Tree Forest Research and Extension Center (TFREC) station in Wenatchee, the daily average global shortwave solar radiation for August 2002 was 259 W/m2. The peak values during daylight hours are typically about three times higher than the daily average. Shortwave solar radiation constitutes the major thermal input to an un-shaded body of water during the day when the sky is clear.
- **Longwave atmospheric radiation.** The longwave radiation from the atmosphere ranges in wavelength from about 4 μm to 120 μm. Longwave atmospheric radiation depends primarily on air temperature and humidity and increases as both of those increase. It constitutes the major thermal input to a body of water at night and on warm cloudy days. The daily average heat flux from longwave atmospheric radiation typically ranges from about 300 to 450 W/m^2 at mid latitudes (Edinger et al., 1974).
- **Longwave back radiation from the water to the atmosphere.** Water sends heat energy back to the atmosphere in the form of longwave radiation in the wavelength range from about 4 μm to 120 μm. Back radiation accounts for a major portion of the heat loss from a body of water. Back radiation increases as water temperature increases. The daily average heat flux out of the water from longwave back radiation typically ranges from about 300 to 500 W/m^2 (Edinger et al., 1974).

An example of the estimated surface heat fluxes in the Wenatchee River near the town of Monitor (RM 7.0) during August 2002 is shown in Figure 4. The daily maximum temperatures in a stream are strongly influenced by removal of riparian vegetation because of diurnal patterns of solar shortwave heat flux (Adams and Sullivan, 1989). The net heat flux into a stream can be managed by increasing the shade from vegetation, which reduces the shortwave solar flux. Other processes – such as longwave radiation, convection, evaporation, bed conduction, or hyporheic exchange – also influence the net heat flux into or out of a stream.

Heat exchange between the stream and the streambed has an important influence on water temperature. The temperature of the streambed is typically warmer than the overlying water at night and cooler than the water during the daylight hours (Figure 5). Heat is typically transferred from the water into the streambed during the day then back into the stream during the night (Adams and Sullivan, 1989). This has the effect of dampening the diurnal range of stream temperature variations without affecting the daily average stream temperature.

The bulk temperature of a vertically mixed volume of water in a stream segment under natural conditions tends to increase or decrease with time during the day according to whether the net heat flux is either positive or negative. When the sun is not shining, the water temperature tends toward the dew-point temperature (Edinger et al., 1974; Brady et al., 1969). The equilibrium temperature of a natural body of water is defined as the temperature at which the water is in equilibrium with its surrounding environment and the net rate of surface heat exchange would be zero (Edinger et al., 1968; Edinger et al., 1974).

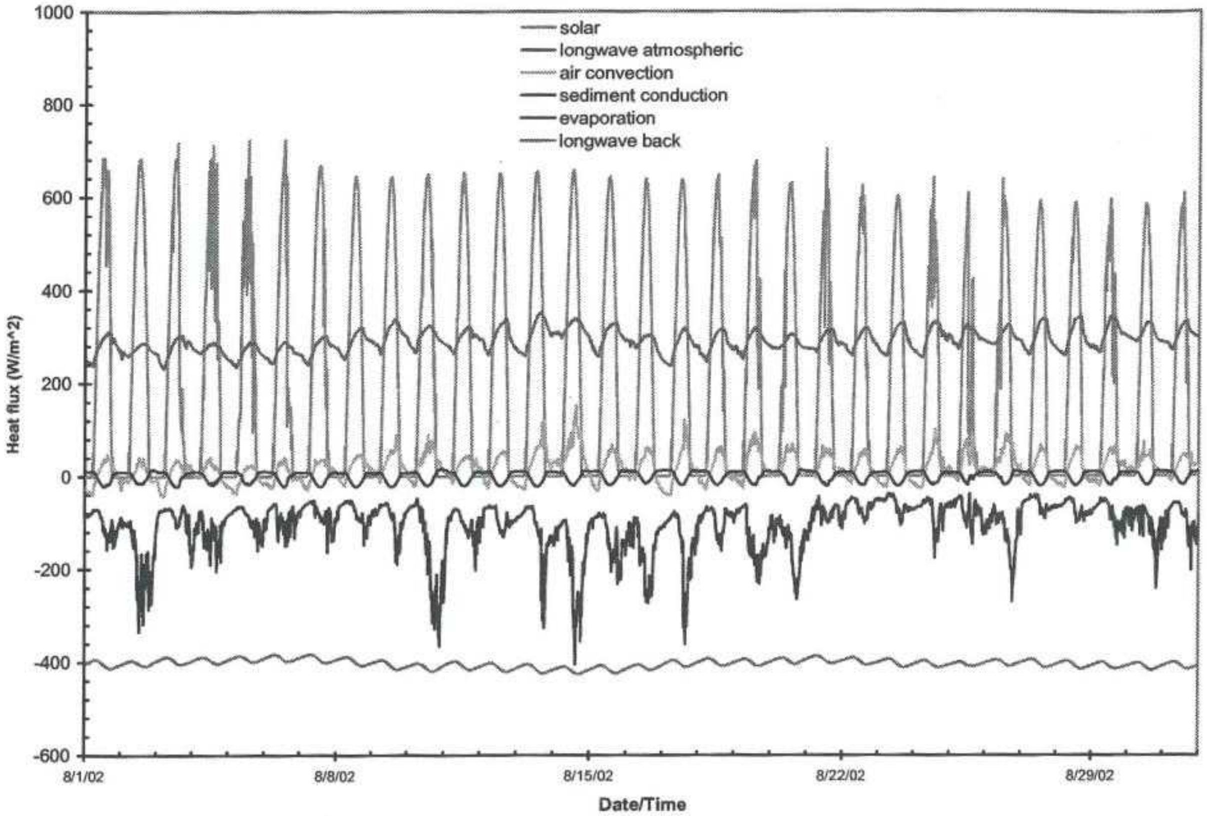


Figure 4. Estimated surface heat fluxes in the Wenatchee River near Monitor (RM 7.0) during August 2002 (net heat flux = solar + longwave atmosphere + longwave back + air convection + evaporation + sediment conduction)

The dominant contribution to the seasonal variations in the equilibrium temperature of water is from seasonal variations in the dew-point temperature (Edinger et al., 1974). The main source of hourly fluctuations in water temperature during the day is solar radiation. Solar radiation generally reaches a maximum during the day when the sun is highest in the sky unless cloud cover or shade from vegetation interferes.

The complete heat budget for a stream also accounts for the mass transfer processes which depend on the amount of flow and the temperature of water flowing into and out of a particular volume of water in a segment of a stream. Mass transfer processes in open channel systems can occur through advection, dispersion, and mixing with tributaries and groundwater inflows and outflows. Mass transfer relates to transport of flow volume downstream, instream mixing, and the introduction or removal of water from a stream. For instance, flow from a tributary will cause a temperature change in the mainstem river if the temperature is different in the two waterbodies.

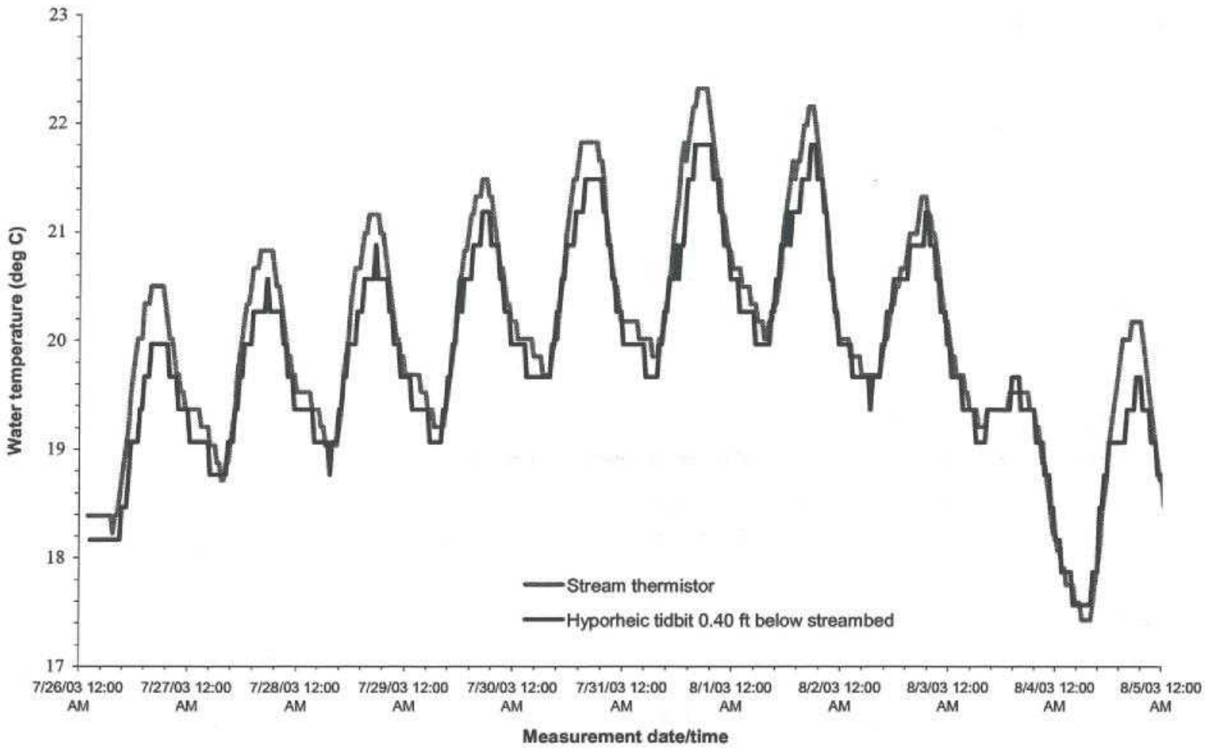


Figure 5. Example of water and streambed temperatures at the end of July and beginning of August 2002 (Wenatchee River at USGS gage near Peshastin, RM 21.5).

Thermal role of riparian vegetation

The role of riparian vegetation in maintaining a healthy stream condition and water quality is well documented and accepted in the scientific literature. Summer stream temperature increases due to the removal of riparian vegetation is well documented (e.g., Holtby, 1988; Lynch et al., 1984; Rishel et al., 1982; Patric, 1980; Swift and Messer, 1971; Brown et al., 1971; and Levno and Rothacher, 1967). These studies generally support the findings of Brown and Krygier (1970) that loss of riparian vegetation results in larger daily temperature variations and elevated monthly and annual temperatures. Adams and Sullivan (1989) also concluded that daily maximum temperatures are strongly influenced by the removal or riparian vegetation because of the effect of diurnal fluctuations in solar heat flux.

Summaries of the scientific literature on the thermal role of riparian vegetation in forested and agricultural areas are provided by Belt et al., 1992; Beschta et al., 1987; Bolton and Monahan, 2001; Castelle and Johnson, 2000; CH2MHill, 2000; GEI, 2002; Ice, 2001; and Wenger, 1999. All of these summaries recognize that the scientific literature indicates that riparian vegetation plays an important role in controlling stream temperature.

The list of important benefits that riparian vegetation has upon the stream temperature includes:

- Near-stream vegetation height, width, and density combine to produce shadows that can reduce solar heat flux to the surface of the water.
- Riparian vegetation creates a thermal microclimate that generally maintains cooler air temperatures, higher relative humidity, lower wind speeds, and cooler ground temperatures along stream corridors.
- Near-stream vegetation increases bank stability. Channel morphology is often highly influenced by land cover type and condition. Near-stream vegetation affects flood plain and instream roughness, contributing coarse woody debris and influencing sedimentation, stream substrate compositions, and streambank stability.

The warming of water temperatures as a stream flows downstream is a natural process. However, the rates of heating can be dramatically reduced when high levels of shade exist and heat flux from solar radiation is minimized. The overriding justification for increases in shade from riparian vegetation is to minimize the contribution of solar heat flux in stream heating. There is a natural maximum level of shade that a given stream is capable of attaining. The importance of shade decreases as the width of a stream increases.

The distinction between reduced heating of streams and actual cooling is important. Shade can significantly reduce the amount of heat flux that enters a stream. Whether there is a reduction in the amount of warming of the stream, maintenance of inflowing temperatures, or cooling of a stream as it flows downstream depends on the balance of all of the heat exchange and mass transfer processes in the stream.

Effective shade

Shade is an important parameter that controls the stream heating derived from solar radiation. Solar radiation has the potential to be one of the largest heat transfer mechanisms in a stream system. Human activities can degrade near-stream vegetation and/or channel morphology, and in turn, decrease shade. Reductions in shade have the potential to cause significant increases in heat delivery to a stream system. Stream shade may be measured or calculated using a variety of methods (Chen, 1996; Chen et al., 1998a,b; Ice, 2001; OWEB, 1999; Teti, 2001).

Shade is the amount of solar energy that is obscured or reflected by vegetation or topography above a stream. Effective shade is defined as the fraction or percentage of the total possible solar radiation heat energy that is prevented from reaching the surface of the water:

$$\text{effective shade} = (J_1 - J_2)/J_1$$

where J_1 is the potential solar heat flux above the influence of riparian vegetation and topography and J_2 is the solar heat flux at the stream surface.

In the Northern Hemisphere, the earth tilts on its axis toward the sun during summer months, allowing longer day length and higher solar altitude, both of which are functions of solar declination (i.e., a measure of the earth's tilt toward the sun) (Figure 6). Geographic position (i.e., latitude and longitude) fixes the stream to a position on the globe, while aspect provides the stream/riparian orientation (direction of streamflow).

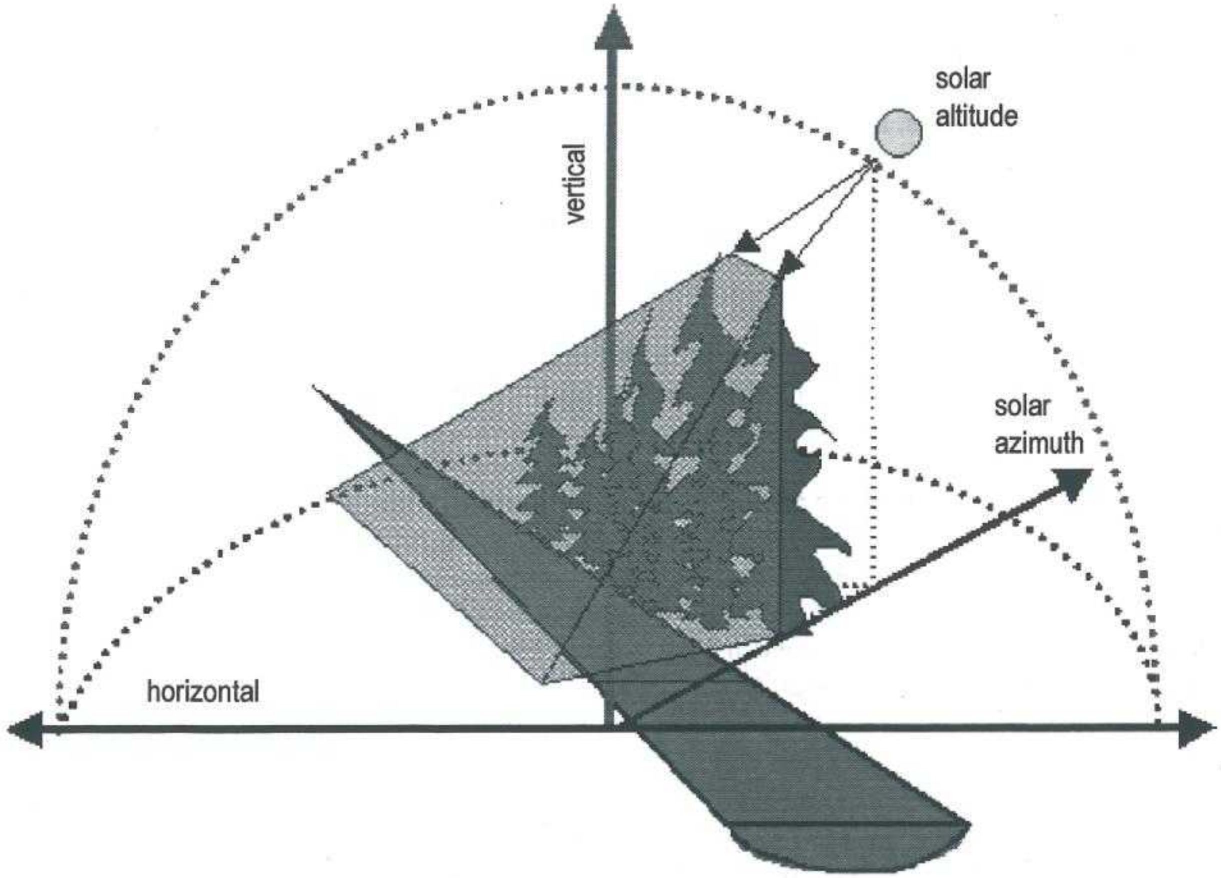


Figure 6. Parameters that affect shade and geometric relationships. Solar altitude is a measure of the vertical angle of the sun's position relative to the horizon. Solar azimuth is a measure of the horizontal angle of the sun's position relative to north.

Near-stream vegetation height, width and density describe the physical barriers between the stream and sun that can attenuate and scatter incoming solar radiation (produce shade) (Table 2). The solar position has a vertical component (solar altitude) and a horizontal component (solar azimuth) that are both functions of time/date (solar declination) and the earth's rotation.

Table 2. Factors that influence stream shade.

Description	Parameter
Season/time	Date/time
Stream characteristics	Aspect, **channel width**
Geographic position	Latitude, longitude
Vegetative characteristics	**Riparian vegetation height, width, and density**
Solar position	Solar altitude, solar azimuth

Bold indicates those factors influenced by human activities.

While the interaction of these shade variables may seem complex, the mathematics that describes them is relatively straightforward geometry. Using solar tables or mathematical simulations, the potential daily solar load can be quantified. The shade from riparian vegetation can be measured with a variety of methods, including (Ice, 2001; OWEB, 1999; Teti, 2001):

- Hemispherical photography
- Angular canopy densiometer
- Solar pathfinder

Hemispherical photography is generally regarded as the most accurate method for measuring shade, although the equipment that is required is significantly more expensive compared with other methods. Angular canopy densiometers (ACD) provide a good balance of cost and accuracy for measuring the importance of riparian vegetation for preventing increases in stream temperature (Teti, 2001; Beschta et al. 1987). Whereas canopy density is usually expressed as a vertical projection of the canopy onto a horizontal surface, the ACD is a projection of the canopy measured at an angle above the horizon at which direct beam solar radiation passes through the canopy. This angle is typically determined by the position of the sun above the horizon during that portion of the day (usually between 10 A.M. and 2 P.M. in mid to late summer) when the potential solar heat flux is most significant. Typical values of the ACD for old-growth stands in western Oregon have been reported to range from 80% to 90%.

Computer programs for the mathematical simulation of shade may also be used to estimate shade from measurements or estimates of the key parameters listed in Table 2 (Ecology, 2003a; Chen, 1996; Chen et al., 1998a,b; Boyd, 1996; Boyd and Park, 1998).

Riparian buffers and effective shade

Trees in riparian areas provide shade to streams and minimize undesirable water temperature changes (Brazier and Brown, 1973; Steinblums et al., 1984). The shading effectiveness of riparian vegetation is correlated to riparian area width (Figure 7). The shade as represented by angular canopy density (ACD), for a given riparian buffer width varies over space and time because of differences among site potential vegetation, forest development stages (e.g., height and density), and stream width. For example, a 50-foot-wide riparian area with fully developed trees could provide from 45% to 72% of the potential shade in the two studies shown in Figure 7.

The Brazier and Brown (1973) shade data show a stronger relationship between ACD and buffer strip width than the Steinblums et al. (1984) data. The r^2 correlation for ACD and buffer width was 0.87 and 0.61 in Brazier and Brown (1973) and Steinblums et al. (1984), respectively. This difference supports the use of the Brazier and Brown curve as a basis for measuring shade effectiveness under various riparian buffer proposals. These results reflect the natural variation among old growth sites studied, and show a possible range of potential shade.

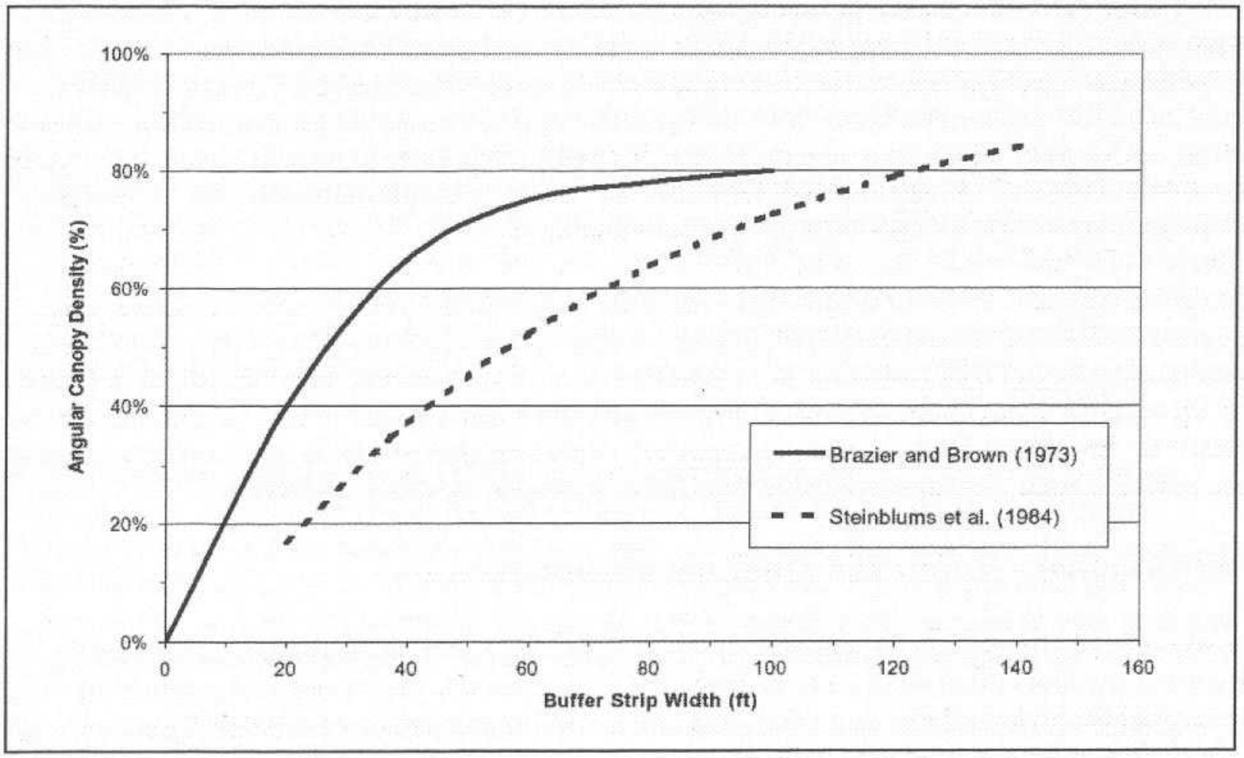


Figure 7. Relationship between angular canopy density and riparian buffer width for small streams in old-growth riparian stands (after Beschta et al., 1987 and CH2MHill, 2000).

Several studies of forest streams report that most of the potential shade comes from the riparian area within about 75 feet (23 m) of the channel (CH2MHill, 2000; Castelle and Johnson, 2000):

- Beschta et al. (1987) report that a 98-foot-wide (30-m) buffer provides the same level of shading as that of an old-growth stand.
- Brazier and Brown (1973) found that a 79-foot (24-m) buffer would provide maximum shade to streams.
- Steinblums et al. (1984) concluded that a 56-foot (17-m) buffer provides 90% of the maximum ACD.
- Corbett and Lynch (1985) concluded that a 39-foot (12-m) buffer should adequately protect small streams from large temperature changes following logging.
- Broderson (1973) reported that a 49-foot (15-m) buffer provides 85% of the maximum shade for small streams.
- Lynch et al. (1984) found that a 98-foot (30-m) buffer maintains water temperatures within 2°F (1°C) of their former average temperature in small streams (channel width less than 3 m).

GEI (2002) reviewed the scientific literature related to the effectiveness of buffers for shade protection in agricultural areas in Washington and concluded that buffer widths of 10 m (33 feet) provide nearly 80% of the maximum potential shade in agricultural areas. Wenger (1999) concluded that a minimum continuous buffer width of 10-30 m should be preserved or restored along each side of all streams on a municipal or county-wide scale to provide stream temperature control and maintain aquatic habitat. GEI (2002) considered the recommendations of Wenger (1999) to be relevant for agricultural areas in Washington.

Steinblums et al. (1984) concluded that that shade could be delivered to forest streams from beyond 75 feet (22 m) and potentially out to 140 feet (43 m). In some site-specific cases, forest practices between 75 and 140 feet from the channel have the potential to reduce shade delivery by up to 25% of maximum. However, any reduction in shade beyond 75 feet would probably be relatively low on the horizon, and the impact on stream heating would be relatively low because the potential solar radiation decreases significantly as solar elevation decreases.

Microclimate - surrounding thermal environment

A secondary consequence of near-stream vegetation is its effect on the riparian microclimate. Riparian corridors often produce a microclimate that surrounds the stream where cooler air temperatures, higher relative humidity, and lower wind speeds are characteristic. Riparian microclimates tend to moderate daily air temperatures. Relative humidity increases result from the evapotranspiration that is occurring by riparian plant communities. Wind speed is reduced by the physical blockage produced by riparian vegetation.

Riparian buffers commonly occur on both sides of the stream, compounding the edge influence on the microclimate. Brosofske et al. (1997) reported that a buffer width of at least 150 feet (45 m) on each side of the stream was required to maintain a natural riparian microclimate environment in small forest streams (channel width less than 4 m) in the foothills of the western slope of the Cascade Mountains in western Washington, with predominantly Douglas-fir and western hemlock.

Bartholow (2000) provided a thorough summary of literature of documented changes to the environment of streams and watersheds associated with extensive forest clearing. Changes summarized by Bartholow (2000) are representative of hot summer days and indicate the mean daily effect unless otherwise indicated:

- **Air temperature**. Edgerton and McConnell (1976) showed that removing all or a portion of the tree canopy resulted in cooler terrestrial air temperatures at night and warmer temperatures during the day, enough to influence thermal cover sought by elk (*Cervus canadensis*) on their eastern Oregon summer range. Increases in maximum air temperature varied from 5 to 7°C for the hottest days (estimate). However, the mean daily air temperature did not appear to have changed substantially since the maximum temperatures were offset by almost equal changes to the minima. Similar temperatures have been commonly reported (Childs and Flint, 1987; Fowler et al., 1987), even with extensive clearcuts (Holtby, 1988). In an evaluation of buffer strip width, Brosofske et al. (1997) found that air temperatures immediately adjacent to the ground increased 4.5°C during the day and about 0.5°C at night (estimate). Fowler and Anderson (1987) measured a 0.9°C air temperature increase in clearcut areas, but temperatures were also 3°C higher in the adjacent forest. Chen et al. (1993) found similar (2.1°C) increases. All measurements reported here were made over land instead of water, but in aggregate support about a 2°C increase in ambient mean daily air temperature resulting from extensive clearcutting.

- **Relative humidity**. Brosofske et al. (1997) examined changes in relative humidity within 17 to 72 m buffer strips. The focus of their study was to document changes along the gradient from forested to clearcut areas, so they did not explicitly report pre- to post-harvest changes at the stream. However, there appeared to be a reduction in relative humidity at the stream of 7% during the day and 6% at night (estimate). Relative humidity at stream sites increased exponentially with buffer width. Similarly, a study by Chen et al. (1993) showed a decrease of about 11% in mean daily relative humidity on clear days at the edges of clearcuts.

- **Wind speed**. Brosofske et al. (1997) reported almost no change in wind speed at stream locations within buffer strips adjacent to clearcuts. Speeds quickly approached upland conditions toward the edges of the buffers, with an indication that wind actually increased substantially at distances of about 15 m from the edge of the strip, and then declined farther upslope to pre-harvest conditions. Chen et al. (1993) documented increases in both peak and steady winds in clearcut areas; increments ranged from 0.7 to 1.2 m/s (estimated).

Spence et al. (1996) also provided a summary of literature related to the influence of riparian vegetation on microclimate as follows:

- Chen (1991) reported that soil and air temperatures, relative wind speed, humidity, soil moisture, and solar radiation all changed with increasing distance from the edges of clearcuts in the western Cascades.

- FEMAT (1993) concluded from Chen's work that the loss of upland forests probably influences conditions within the riparian zone. FEMAT also suggested that riparian buffers for maintaining microclimates need to be wider than those for protecting other riparian functions.

Thermal role of channel morphology

Changes in channel morphology (widening) affect stream temperatures. As a stream widens, the surface area exposed to heat flux increases, resulting in increased energy exchange between a stream and its environment (Chapra, 1997). Further, wide channels are likely to have decreased levels of shade due to the increased distance created between vegetation and the wetted channel and the decreased fraction of the stream width that could potentially be covered by shadows from riparian vegetation. Conversely, narrow channels are more likely to experience higher levels of shade.

Channel widening is often related to degraded riparian conditions that allow increased streambank erosion and sedimentation of the streambed, both of which correlate strongly with riparian vegetation type and condition (Rosgen, 1996). Channel morphology is not solely dependent on riparian conditions. Sedimentation can deposit material in the channel, fill pools, and aggrade the streambed, reducing channel depth and increasing channel width.

Channel modification usually occurs during high flow events. Land uses that affect the magnitude and timing of high flow events may negatively impact channel width and depth. Riparian vegetation conditions will affect the resilience of the streambanks/flood plain during periods of sediment introduction and high flow. Disturbance processes may have differing results depending on the ability of riparian vegetation to shape and protect channels. Channel morphology is related to riparian vegetation composition and condition by:

- **Building streambanks**. Trap suspended sediments, encourage deposition of sediment in the flood plain, and reduce incoming sources of sediment.
- **Maintaining stable streambanks**. High rooting strength and high streambank and flood plain roughness prevent streambank erosion.
- **Reducing flow velocity** (erosive kinetic energy). Supplying large woody debris to the active channel, high pool:riffle ratios and adding channel complexity reduce flow velocities.

Pollutant sources

The pollutants targeted in this TMDL are heat from anthropogenic increases in solar radiation loading to the stream network, and heat from warm water discharges of human origin.

Riparian vegetation, stream morphology, hydrology, climate, and geographic location influence stream temperature. While climate and geographic location are outside of human control, riparian condition, channel morphology, and hydrology are affected by land use activities.

Low summertime flows decrease the thermal assimilative capacity of streams. Pollutant loading causes larger temperature increases in stream segments where flows are reduced.

Heat loading from point sources occurs when waters with differing temperatures are mixed. Wasteload allocations are developed for point sources that discharge to temperature-impaired waterbodies or discharge into waterbodies that drain to temperature-impaired waterbodies.

Pollutants and surrogate measures

Heat loads to the stream are calculated in this TMDL in units of calories per square centimeter per day or watts per square meter (W/m^2). However, heat loads are of limited value in guiding management activities needed to solve identified water quality problems.

The Wenatchee River temperature TMDL will incorporate measures other than "daily loads" to fulfill the requirements of Section 303(d). This TMDL allocates other appropriate measures, or "surrogate measures," as provided under EPA regulations [40 CFR 130.2(i)]. The "Report of the Federal Advisory Committee on the Total Maximum Daily Load (TMDL) Program" (EPA, 1998) includes the following guidance on the use of surrogate measures for TMDL development:

"When the impairment is tied to a pollutant for which a numeric criterion is not possible, or where the impairment is identified but cannot be attributed to a single traditional "pollutant," the state should try to identify another (surrogate) environmental indicator that can be used to

develop a quantified TMDL, using numeric analytical techniques where they are available, and best professional judgment (BPJ) where they are not."

Water temperature increases as a result of increased heat flux loads. A loading capacity for radiant heat energy (e.g., incoming solar radiation) can be used to define a reduction target that forms the basis for identifying a surrogate for heat loading from solar radiation. This technical assessment for the Wenatchee River temperature TMDL uses effective shade as a surrogate measure of heat flux from solar radiation to fulfill the requirements of Section 303(d). Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface. The definition of effective shade allows direct translation of the solar radiation loading capacity.

Because factors that affect water temperature are interrelated, the surrogate measure (effective shade) relies on restoring/protecting riparian vegetation to increase stream surface shade levels, reducing streambank erosion, stabilizing channels, reducing the near-stream disturbance zone width, and reducing the surface area of the stream exposed to radiant processes. Effective shade screens the water's surface from direct rays of the sun. Other factors influencing heat flux and water temperature were also considered, including microclimate, channel geometry, groundwater recharge, and instream flow.

Background

The Wenatchee River basin (WRIA 45) encompasses 878,423 acres and is located in the central part of Washington State. The subbasin is bounded on the west by the Cascade Mountains, on the north and east by the Entiat Mountains, and on the south by the Wenatchee Mountains. The Wenatchee is a subbasin to the Columbia River and enters that system at the city of Wenatchee 15 miles upstream of the Rock Island Dam. The geology of the upper subbasin consists of high and low relief land types associated with glaciation (e.g., cirque headwalls, glaciated ridges, and glacial/fluvial outwash). The middle part of the subbasin is a mixture of igneous and basalt rock formations and glacial/fluvial outwash terraces. Alluvial fans and terraces are predominant land types in the lower Wenatchee (USDA Forest Service, 1999).

Annual average precipitation throughout the subbasin ranges from 150 inches at the crest of the Cascades to 8.5 inches in Wenatchee (USDA Forest Service, 1999; Figure 8). Streamflow varies during the year, but mean monthly discharge peaks in the spring from combined effects of snowmelt and rain on snow events.

Most of the annual streamflow in the Wenatchee River originates from tributaries in the upper subbasin: the White River (25%), Icicle Creek (20%), Nason Creek (18%), the Chiwawa River (15%), and the Little Wenatchee River (15%) (Andonaegui, 2001). Both the White and the Little Wenatchee rivers enter Lake Wenatchee in the upper subbasin; the mouth of the lake is the head of the Wenatchee River, and Nason Creek enters the river just below the lake outlet.

Land cover in the Wenatchee River watershed is shown in Table 3 (USGS, 1999).

Table 3. Land cover in the Wenatchee River watershed.

Land type	Area Km^2	Percent of total
Water	52.29	1.5%
Developed	15.03	0.4%
Barren	245.77	7.1%
Forested upland	2409.44	69.4%
Shrubland	281.13	8.1%
Orchard/vineyard/other non-natural woody	48.74	1.4%
Herbaceous upland	409.42	11.8%
Herbaceous planted/cultivated	5.16	0.1%
Wetlands	6.02	0.2%
Total	3473.00	

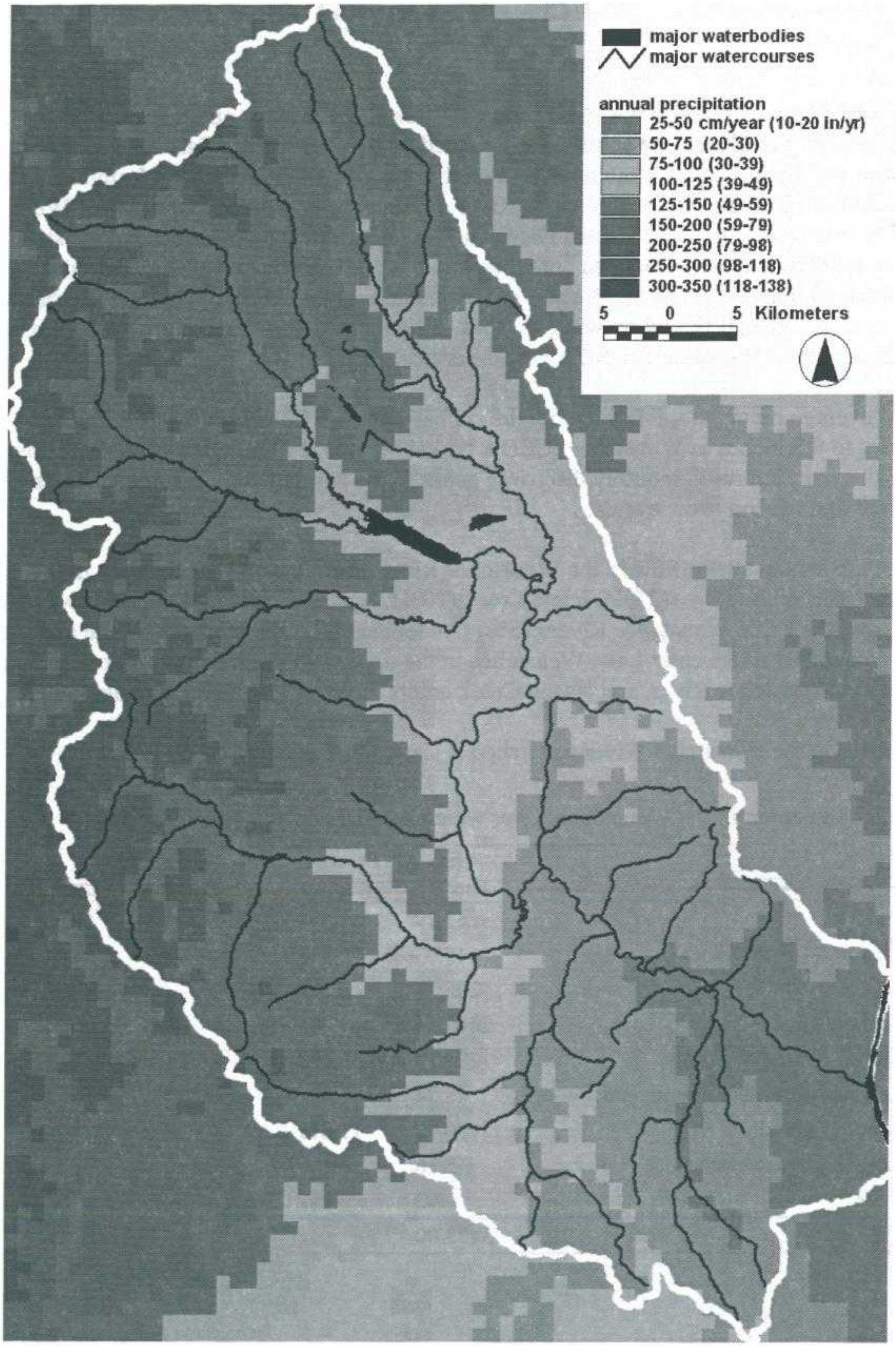


Figure 8. Annual average precipitation in the Wenatchee River watershed (data from www.daymet.org).

Land ownership

There is a mixture of federal, state, county, and private land ownership throughout the subbasin. Most of the upper subbasin is designated federal wilderness area and is under the jurisdiction of the U.S. Forest Service Lake Wenatchee and Leavenworth Ranger Districts. East of Peshastin, state highways 2 and 97 parallel much of the Wenatchee mainstem and Nason Creek and contain portions of their streambanks. The incorporated cities designated in the 2000 census are Wenatchee (population 27,856), Cashmere (population 2,965), and Leavenworth (population 2,074). There are smaller unincorporated towns and communities located along State Highways 2 and 97 (2000 census information).

Forest land cover

Most of the land area in the Wenatchee River watershed is covered with forest (Table 3). Federally owned forest land is managed according to the USFS Forest Plan. A technical report published by Ecology in 2003 presents the TMDL for water temperature and the load allocations that are required on forest land owned and managed by the USFS in the Wenatchee National Forest (Whiley and Cleland, 2003).

Forest land in the watershed that is not owned and managed by the USFS is subject to the Washington State Department of Natural Resources (DNR) Forest and Fish Report.

USFS Forest Plan

Forest plans are required by the National Forest Management Act (NFMA) for each national forest. These plans establish land allocations, goals and objectives, and standards and guidelines that direct how National Forest System lands are managed.

The Aquatic Conservation Strategy, a component of the amended forest plan, is designed to protect and restore the ecological health of the aquatic system and its dependent species. Restoration priorities are based on watershed analysis and planning which will help to determine areas where the greatest benefits can be achieved along with the likelihood of success. In general, watersheds that currently have the best habitat, or those with the greatest potential for recovery, are priority areas for increased protection and for restoration treatments. The conservation strategy aims to maintain the natural disturbance regime.

Components of the Aquatic Conservation Strategy include:

- *Riparian Reserves:* Lands along streams, wetlands, ponds, lakes, and unstable and potentially unstable areas where special standards and guidelines direct land use. Riparian reserves are designed to maintain and restore the ecological health of watersheds and aquatic ecosystems. Interim widths for riparian reserves are established based on ecological, hydrologic, and geomorphic factors. Interim riparian reserves for federal lands are delineated as part of the watershed analysis process based on identification and evaluation of critical hillslope, riparian, and channel processes. Final riparian reserve boundaries are determined at the site-specific level during the appropriate National Environmental Policy Act analysis.

- *Key Watersheds:* A system of refugia comprising watersheds crucial to at-risk fish species and stocks while also providing high quality habitat. Key watersheds are generally those identified as having the best habitat or those with the greatest potential for recovery. Key watersheds are priority areas for increased protection and for restoration treatments. Activities to protect and restore aquatic habitat in key watersheds are a higher priority than similar activities in other watersheds.

- *Watershed Analysis:* An on-going, iterative analysis procedure for characterizing watershed and ecological processes to meet specific management objectives within the subject watershed. This analysis should enable watershed planning that achieves Aquatic Conservation Strategy objectives. Watershed analysis provides the basis for monitoring and restoration programs and the foundation from which the riparian reserves can be delineated.

- *Watershed Restoration:* A comprehensive, long-term program of watershed restoration to restore watershed health and aquatic ecosystems, including habitats supporting fish and other aquatic and riparian-dependent organisms.

Riparian reserves are specified for categories of streams or waterbodies as follows:

- Fish-bearing streams - Riparian reserves consist of the stream and the area on each side of the stream extending from the edges of the active stream channel to the top of the inner gorge, or to the outer edges of the 100-year flood plain, or to the outer edges of riparian vegetation, or to a slope distance equal to the height of two site-potential trees, or 300 feet slope distance (600 feet total, including both sides of the stream channel), whichever is greatest.

- Permanently flowing non-fish-bearing streams - Riparian reserves consist of the stream and the area on each side of the stream extending from the edges of the active stream channel to the top of the inner gorge, or to the outer edges of the 100-year flood plain, or to the outer edges of riparian vegetation, or to a slope distance equal to the height of one site-potential tree, or 150 feet slope distance (300 feet total, including both sides of the stream channel), whichever is greatest.

- Specific riparian reserves ranging from 100 to 300 feet of slope distance are also specified for the following categories of riparian areas: constructed ponds and reservoirs; wetlands (greater than one acre), lakes, and natural ponds; seasonally flowing or intermittent streams; wetlands less than one acre; and unstable and potentially unstable areas.

Additional measures are being undertaken within the Wenatchee Forest through a roads analysis. The objective of the roads analysis is to provide critical information needed to identify and manage a minimum road system that is safe and responsive to public needs while having minimal adverse effects on ecological processes and health. This planning action is being accomplished with public and agency (federal and state) input.

Water Quality Restoration Plans are Forest Service planning documents that identify Best Management Practice actions appropriate to correct water quality issues within defined drainage areas. These plans will enhance and focus activities to improve shade levels in areas where the plans are developed.

Ecology staff are involved in review of USFS planning and implementation activities to ensure that state water quality laws and regulations are being met or exceeded. This includes the responsibility to certify that general water quality Best Management Practices (BMPs) and current Forest Plans are consistent with the federal Clean Water Act. The certification process includes the comparison of state BMPs and USFS BMPs. If Ecology or the USFS determines that USFS BMPs provide less resource protection than state BMPs, the USFS will review their BMPs for amendment.

TFW and the Forest and Fish Report

In 1986, as an alternative to competitive lobbying and court cases, four caucuses (the Tribes, the timber industry, the state, and the environmental community) decided to try to resolve contentious forest practices problems on non-federal land through negotiations. This resulted in the first Timber Fish Wildlife (TFW) agreement in February 1987. Subsequent events caused the TFW caucuses to again come together at the policy level to address a new round of issues. Under the U.S. Endangered Species Act, several salmonid populations have been listed or considered for listing. In addition, over 660 Washington streams have been included on a 303(d) list identifying stream segments with water quality problems under the Clean Water Act.

In November 1996, the caucuses – now expanded from the original four to six with the addition of federal and local governments – decided to work together to develop joint solutions to these problems. The Forest and Fish Report was presented to the Forest Practices Board of the state Department of Natural Resources and the Governor's Salmon Recovery Office in February 1999 (www.wa.gov/dnr/htdocs/fp/fpb/forests&fish.html). The goals of the forestry module of the Forest and Fish Report are fourfold:

1. Provide compliance with the Endangered Species Act for aquatic and riparian-dependent species on non-federal forest lands.
2. Restore and maintain riparian habitat on non-federal forest lands to support a harvestable supply of fish.
3. Meet the requirements of the Clean Water Act for water quality on non-federal forest lands.
4. Keep the timber industry economically viable in the State of Washington.

To achieve the overall objectives of the Forest and Fish Initiative, significant changes in current riparian forest management policy are prescribed. The goal of riparian management and conservation as recommended in the Forest and Fish Report is to achieve restoration of high levels of riparian function and maintenance of these levels once achieved.

Desired future conditions are the stand conditions of a mature riparian forest, agreed to be 140 years of age (the midpoint between 80 and 200 years) and the attainment of resource objectives. For forests in eastern Washington, such as the forest land in the Wenatchee River watershed, riparian management is intended to provide stand conditions that vary over time within a range that meets functional conditions and maintains general forest health. These desired future conditions are a reference point on the pathway to restoration of riparian functions, not an endpoint of riparian stand development.

The riparian functions addressed by the recommendations in the Forest and Fish Report include bank stability, the recruitment of woody debris, leaf litter fall, nutrients, sediment filtering, shade, and other riparian features that are important to both riparian forest and aquatic system conditions. The diversity of riparian forests across the landscapes is addressed by tailoring riparian prescriptions to the site productivity and tree community at specific sites.

Load allocations are included in a TMDL for forest lands in the Wenatchee River basin will be proposed in accordance with the section of Forest and Fish entitled "TMDLs produced prior to 2009 in mixed use watersheds". Also consistent with the Forest and Fish Agreement, implementation of the load allocations established in this TMDL for private and state forestlands will be accomplished via implementation of the revised forest practice regulations. The effectiveness of the Forest and Fish Rules will be measured through the adaptive management process and monitoring of streams in the watershed.

The state Department of Natural Resources (DNR) is encouraged to condition forest practices to prohibit any further reduction of stream shade and not waive or modify any shade requirements for timber harvesting activities on state and private lands. Ecology is committed in assisting DNR in identifying those site-specific situations where reduction of shade has the potential for or could cause material damage to public resources.

New emergency rules for roads also apply. These include new road construction standards, as well as new standards and a schedule for upgrading existing roads. Under the new rules, roads must provide for better control of road-related sediments, provide better streambank stability protection, and meet current Best Management Practices. DNR is also responsible for oversight of these activities.

The Department of Ecology policy for considering the Forest and Fish Report in temperature TMDLs is as follows: Load allocations in the technical report are generally established in accordance with Schedule M-2 of the Forest and Fish Report, February 1999 (www.wa.gov/dnr/htdocs/fp/fpb/forests&fish.html). Also consistent with the Forest and Fish Agreement, implementation of the load allocations for private and state forest lands are generally accomplished via implementation of the revised forest practice regulations. The effectiveness of the Forest and Fish Rules are generally measured through the adaptive management processes and monitoring of streams in the watershed. If shade is not moving on a path toward the TMDL load allocation by 2009, Ecology's policy is to suggest changes to the Forest Practices Board.

Other regulations affecting riparian land use

For private land that is neither federal forest nor covered by the Forest and Fish Report (i.e., private and state-owned forest), some regulations affect land use and management along rivers and streams:

- Shorelines of rivers with annual flows greater than 1,000 cfs, and streams with average flows greater than 20 cfs, are managed under the Shoreline Management Act.
- Within municipal boundaries, land management practices next to streams may be limited if there is a local critical areas ordinance.

- Outside municipalities, county sensitive areas ordinances may affect such practices as grading or clearing next to a stream, if the activity comes under county review as part of a permit application.

Instream flow rule for the Wenatchee River

Instream flows and water withdrawals are managed through regulatory avenues separate from TMDLs. However, stream temperature is related to the amount of instream flow, and increases in flow generally result in decreases in maximum temperatures. The complete heat budget for a stream segment accounts for the amount of flow and the temperature of water flowing into and out of the stream.

The primary statutes relating to flow in Washington State are as follows:

- Water Code, Chapter 90.03 RCW (1917), section 247, describes Ecology's exclusive authority for setting flows and describes specific conditions on permits stating where flows must be met. It requires consultation with the Department of Fish and Wildlife, the Department of Community, Trade, and Economic Development, the Department of Agriculture, as well as affected Indian Tribes on the establishment of "minimum flows".
- Construction Projects in State Waters, Chapter 77.55 RCW (formerly 75.20)(1949), section 050, requires Ecology to consult with the Department of Fish and Wildlife prior to making a decision on any water right application that may affect flows for food and game fish. Fish and Wildlife may recommend denial or conditioning of a water right permit.
- Minimum Water Flows and Levels Act, Chapter 90.22 RCW (1967), sets forth a process for protecting instream flows through adoption of rules. Among other provisions, it says Ecology must consult with the Department of Fish and Wildlife and conduct public hearings.
- Water Resources Act of 1971, Chapter 90.54 RCW, particularly section 020, includes language that says "base flows" are to be retained in streams except where there are "overriding considerations of the public interest". Further, waters of the state are to be protected and used for the greatest benefit to the people, and water allocation is to be generally based on the securing of "maximum net benefits" to the people of the state. This Act also authorizes Ecology to reserve waters for future beneficial uses.
- In 1998, the Legislature passed Engrossed Substitute House Bill 2514, which was codified as "Watershed Planning," Chapter 90.82 RCW. This chapter provides an avenue for local citizens and various levels of governments to be involved in collaborative water management, including the option of establishing or amending instream flow rules. The watershed planning process specifies that local watershed planning groups can recommend instream flows to Ecology for rule-making, and directs Ecology to undertake rule-making to adopt flows upon receiving such a recommendation.

Under state laws, Ecology oversees both the appropriation of water for out-of-stream uses (e.g., irrigation, municipalities, commercial and industrial uses) and the protection of instream uses (e.g., water for fish habitat and recreational use). Ecology does this by adopting and enforcing regulations, as well as by providing assistance to citizens regarding both public and private water management issues.

Ecology is required by law to protect instream flows by adopting regulations and to manage water uses that affect streamflow. To develop an "instream flow rule" which sets for a particular stream the minimum flows needed during critical times of year, Ecology considers existing flow data, the hydrology of a stream and its natural seasonal flow variation, fish habitat needs, and other factors. Once adopted, an instream flow rule acquires a priority date similar to that associated with a water right. Water rights existing at the time an instream flow rule is adopted are unaffected by the rule, and those issued after rule adoption are subject to the requirements of the rule.

Applicable Water Quality Criteria

Current water quality criteria

This TMDL report is designed to address impairments of characteristic uses caused by high temperatures. The characteristic uses designated for protection in Wenatchee River basin streams are as follows (Chapter 173-201A WAC):

> "Characteristic uses. Characteristic uses shall include, but not be limited to, the following:
> (i) Water supply (domestic, industrial, agricultural).
> (ii) Stock watering.
> (iii) Fish and shellfish:
> Salmonid migration, rearing, spawning, and harvesting.
> Other fish migration, rearing, spawning, and harvesting.
> Clam and mussel rearing, spawning, and harvesting.
> Crayfish rearing, spawning, and harvesting.
> (iv) Wildlife habitat.
> (v) Recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment).
> (vi) Commerce and navigation."

The characteristics uses that are of the most concern in this TMDL are salmonid and other fish migration, rearing, spawning, and harvesting.

The state water quality standards describe criteria for temperature for the protection of characteristic uses. Streams in the Wenatchee River basin are designated as either Class AA or Class A. The definitions of Class AA and A are as follows:

- Class AA waters typically exhibit extraordinary water quality that markedly and uniformly exceeds the requirements for all or substantially all uses.
- Class A waters typically exhibit excellent water quality that meets or exceeds the requirements for all or substantially all uses.

The temperature criteria for Class AA waters are as follows:

> "Temperature shall not exceed 16.0°C...due to human activities. When natural conditions exceed 16.0°C..., no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3°C."

The temperature criteria for Class A waters are as follows:

> "Temperature shall not exceed 18.0°C...due to human activities. When natural conditions exceed 18.0°C..., no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3°C."

During critical periods, natural conditions may exceed the numeric temperature criteria mandated by the water quality standards. In these cases, the antidegradation provisions of those standards apply.

> "Whenever the natural conditions of said waters are of a lower quality than the criteria assigned, the natural conditions shall constitute the water quality criteria."

2003 revised water quality criteria

Ecology is in the process of changing the water quality criteria for temperature. The TMDL will be written to meet the water quality criteria that are in effect at the time the final document is published (or submitted to EPA for approval). The proposed revised 2003 criteria for temperature are described in the following excerpt from the criteria document:

(c) **Aquatic life temperature criteria.** Except where noted, water temperature is measured by the 7-day average of the daily maximum temperatures (7-DADMax). Table 200 (1)(c) lists the temperature criteria for each of the aquatic life use categories.

Table 200 (1)(c). Aquatic Life Temperature Criteria in Fresh Water
(*note: only categories applicable in WRIA 45 are shown*)

Category	Highest 7-DADMax
Char	12°C (53.6°F)
Salmon and Trout Spawning, **Core** Rearing, and Migration	16°C (60.8°F)
Salmon and Trout Spawning, **Noncore** Rearing, and Migration	17.5°C (63.5°F)

(i) When a water body's temperature is warmer than the criteria in Table 200 (1)(c) (or within 0.3°C (0.54°F) of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the 7-DADMax temperature of that water body to increase more than 0.3°C (0.54°F).

(ii) When the natural condition of the water is cooler than the criteria in Table 200 (1)(c), the allowable rate of warming up to, but not exceeding, the numeric criteria from human actions is restricted as follows:
(A) Incremental temperature increases resulting from individual point source activities must not, at any time, exceed 28/(T+5) as measured at the edge of a mixing zone boundary (where "T" represents the background temperature as measured at a point or points unaffected by the discharge and representative of the highest ambient water temperature in the vicinity of the discharge); and
(B) Incremental temperature increases resulting from the combined effect of all nonpoint source activities in the water body must not, at any time, exceed 2.8°C (5.04°F).

(iii) Temperatures are not to exceed the criteria at a probability frequency of more than once every ten years on average.

(iv) Spawning and incubation protection. Where the department determines the temperature criteria established for a water body would likely not result in protective spawning and incubation temperatures, the following criteria apply:
• Maximum 7-DADMax temperatures of 9°C (48.2°F) at the initiation of spawning and at fry emergence for char; and
• Maximum 7-DADMax temperatures of 13°C (55.4°F) at the initiation of spawning for salmon and at fry emergence for salmon and trout.
The two criteria above are protective of incubation as long as human actions do not significantly disrupt the normal patterns of fall cooling and spring warming that provide significantly colder temperatures over the majority of the incubation period. The department will maintain a list of waters where the single-summer maximum criterion is not sufficient to protect spawning and incubation.

(v) For lakes, human actions considered cumulatively may not increase the 7-DADMax temperature more than 0.3°C (0.54°F) above natural conditions.

(vi) Temperature measurements should be taken to represent the dominant aquatic habitat of the monitoring site. This typically means samples should:
(A) Be taken from well mixed portions of rivers and streams; and
(B) Not be taken from shallow stagnant backwater areas, within isolated thermal refuges, at the surface, or at the water's edge.

(vii) The department will incorporate the following guidelines on preventing acute lethality and barriers to migration of salmonids into determinations of compliance with the narrative requirements for use protection established in this chapter (e.g., WAC 173-201A-310(1), 173-201A-400(4), and 173-201A-410 (1)(c)). The following site-level considerations do not, however, override the temperature criteria established for waters in subsection (1)(c) of this section or WAC 173-201A-602:
(A) Moderately acclimated (16-20°C, or 60.8.68°F) adult and juvenile salmonids will generally be protected from acute lethality by discrete human actions maintaining the 7-DADMax temperature at or below 22°C (71.6°F) and the 1-day maximum (1-DMax) temperature at or below 23°C (73.4°F).
(B) Lethality to developing fish embryos can be expected to occur at a 1-DMax temperature greater than 17.5°C (63.5°F).
(C) To protect aquatic organisms, discharge plume temperatures must be maintained such that fish could not be entrained (based on plume time of travel) for more than two seconds at temperatures above 33°C (91.4°F) to avoid creating areas that will cause near instantaneous lethality.
(D) Barriers to adult salmonid migration are assumed to exist any time the 1-DMax temperature is greater than 22°C (71.6°F) and the adjacent downstream water temperatures are 3°C (5.4°F) or more cooler.

(viii) Nothing in this chapter shall be interpreted to prohibit the establishment of effluent limitations for the control of the thermal component of any discharge in accordance with 33 U.S.C. 1326 (commonly known as section 316 of the Clean Water Act).

All streams and rivers in the study area that are Class AA under the current criteria will be designated "core" under the 2003 revised criteria [see Table 200(1)(c) above], and Class A will be designated "non-core" except for the specific designations listed in Appendix A.

Seasonal Variation

Clean Water Act Section 303(d)(1) requires that TMDLs "be established at the level necessary to implement the applicable water quality standards with seasonal variations". The current regulation also states that determination of "TMDLs shall take into account critical conditions for streamflow, loading, and water quality parameters" [40 CFR 130.7(c)(1)]. Finally, Section 303(d)(1)(D) suggests consideration of normal conditions, flows, and dissipative capacity.

Existing conditions for stream temperatures in the Wenatchee River watershed reflect seasonal variation. Cooler temperatures occur in the winter, while warmer temperatures are observed in the summer. The highest temperatures typically occur from mid-July through mid-August. This timeframe is used as the critical period for development of the TMDL.

Seasonal estimates for streamflow, solar flux, and climatic variables for the TMDL are taken into account to develop critical conditions for the TMDL model. The critical period for evaluation of solar flux and effective shade will be assumed to be August 1 because it is the mid-point of the period when water temperatures are typically at their seasonal peak.

Critical streamflows for the TMDL were considered to be the lowest 7-day average flows with a 2-year recurrence interval (7Q2), and 10-year recurrence interval (7Q10) for July and August. The 7Q2 streamflow is assumed to represent conditions that would occur during a typical climatic year, and the 7Q10 streamflow is assumed to represent a reasonable worst-case climatic year.

Technical Analysis

Stream heating processes

Riparian vegetation, stream morphology, hydrology, climate, and geographic location influence stream temperature. While climate and geographic location are outside of human control, riparian condition, channel morphology, and hydrology are affected by land use activities. Specifically, the elevated summertime stream temperatures attributed to anthropogenic sources in the Wenatchee River basin result from the following:

- Riparian vegetation disturbance reduces stream surface shading via decreased riparian vegetation height, width, and/or density, thus increasing the amount of solar radiation reaching the stream surface.
- Channel widening reduces the stream depth and increases the stream surface area exposed to energy processes, namely solar radiation.
- Reduced summertime baseflows may result from instream withdrawals and hydraulically connected groundwater withdrawals. Reducing the amount of water in a stream can increase stream temperature (Brown, 1972). Baseflows could also have been reduced due to an increase in impervious surface area from changes in land cover in the watershed.

Current conditions

Meteorology

Regional air temperature, dewpoint temperature, and solar radiation during July-September 2002 and July-September 2003 are shown in Figures 9 and 10. Highest daily average stream temperatures occurred during the period of relatively high air temperatures in mid-August 2002 and the end of July 2003.

Water temperature data – continuous dataloggers

A network of continuous temperature dataloggers was installed in the Wenatchee River watershed by Ecology as described by Bilhimer et al. (2002). Data from 2002 and 2003 show that water temperatures in excess of the current Class A or AA standards and proposed core/ non-core standards are common throughout the watershed (Tables 4 and 5).

Figures 11 and 12 summarize the highest daily maximum and the highest seven-day average maximum water temperatures for 2002 and 2003, respectively. Figures 13-19 present continuous daily maximum water temperatures during July-September at each of the sampling locations during 2002 and 2003.

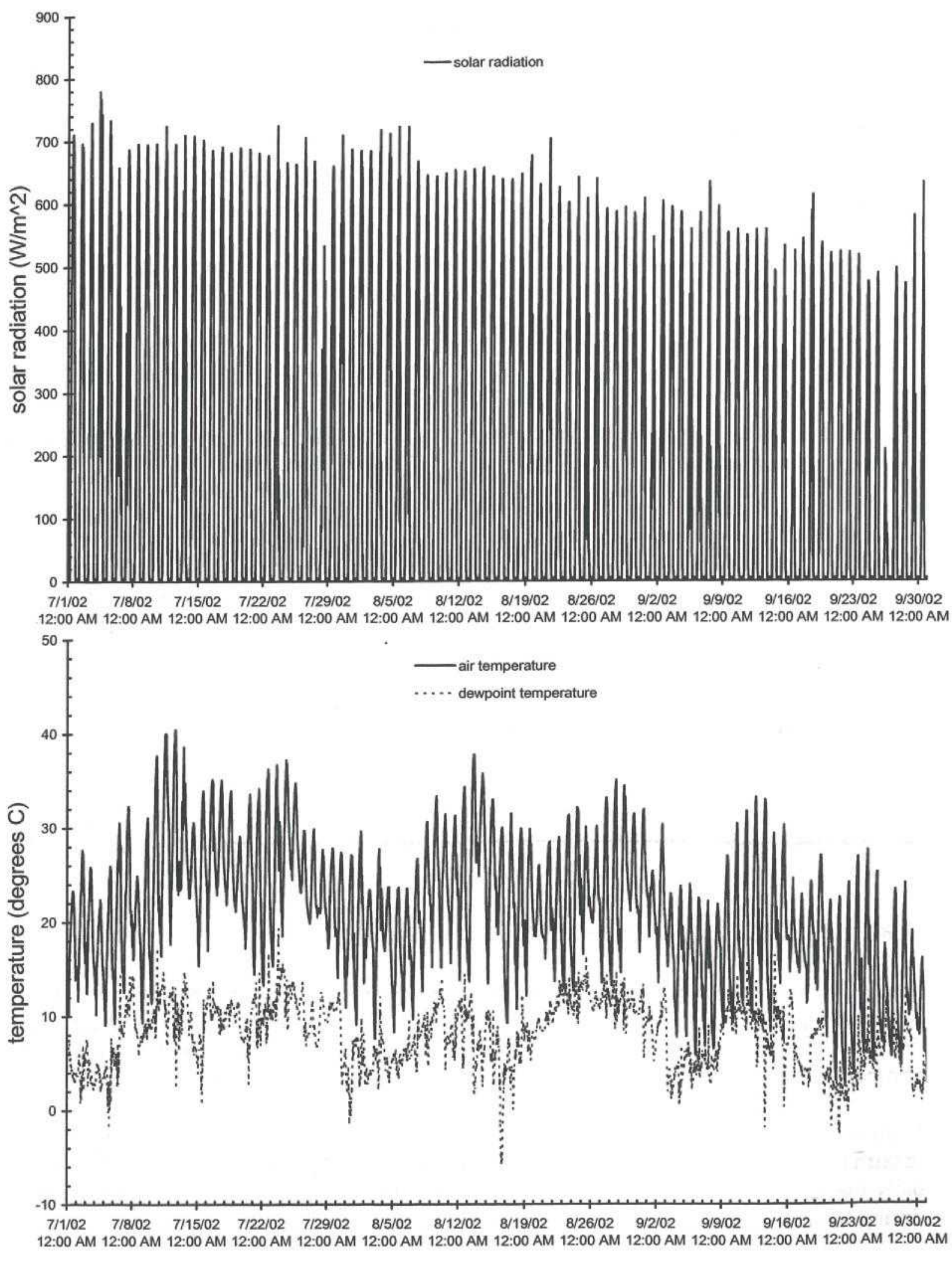


Figure 9. Regional solar radiation, air temperatures, and dewpoint temperatures (at the Wenatchee WSU TFREC station) during July-September 2002.

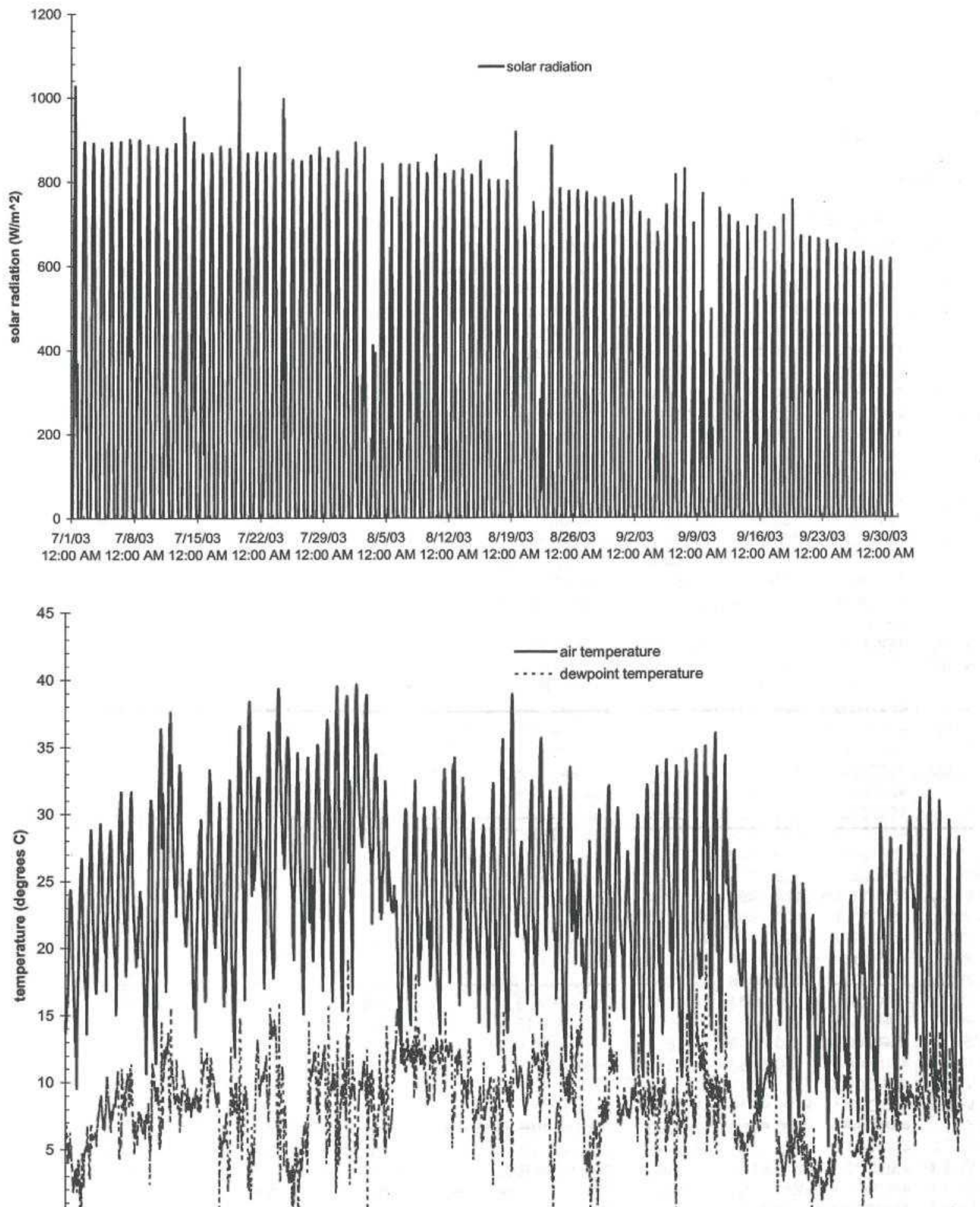


Figure 10. Regional solar radiation, air temperatures, and dewpoint temperatures (at the Wenatchee WSU TFREC station) during July-September 2003.

Table 4. Summary of maximum water temperatures in the Wenatchee basin during 2002.

Agency (1)	Station	Longitude (decimal degrees)	Latitude (decimal degrees)	Description	Water Quality Class	Highest 7-day average daily maximum water temperature during 2002 (deg C)		Highest daily maximum water temperature during 2002 (deg C)	
Ecy WSU	45FL00.3	-120.6947	47.8181	Fish Lake outlet	AA	23.1		23.7	
Ecy WSU	45PC00.3	-120.5789	47.5578	Peshastin RM0.3	A	22.1		23.4	
Ecy WSU	45HR00.1	-120.3492	47.4658	Highline ditch return	A	21.9		25.5	
Ecy WSU	45WR05.3	-120.4142	47.4883	Wenatchee RM05.3	A	21.6		22.2	
Ecy WSU	45WR00.5	-120.3313	47.4572	Wenatchee RM00.5	A	21.4		22.1	
Ecy WSU	45WR10.2	-120.4808	47.5231	Wenatchee RM10.2	A	21.3		21.8	
Ecy WSU	45WR18.7	-120.5920	47.5701	Wenatchee RM18.7	A	21.1		21.8	
Ecy WSU	45MC00.1	-120.4749	47.5213	Mission RM0.1	A	21.0		22.2	
Ecy WSU	45WR14.1	-120.5478	47.5333	Wenatchee RM14.1	A	20.9		21.4	
Ecy WSU	45WR18.1	-120.5809	47.5650	Wenatchee RM18.1	A	20.4		20.8	
Ecy WSU	45WR20.9	-120.6135	47.5823	Wenatchee RM20.9	A	19.9		20.3	
Ecy WSU	45WR49.1	-120.6491	47.7937	Wenatchee RM49.1	AA	19.9		20.6	
Ecy WSU	45WR35.9	-120.7267	47.6791	Wenatchee RM35.9	AA	19.7		20.2	
USFS	45NC00.4	-120.7124	47.8053	Nason RM0.4	AA	19.4	above non-core	20.0	
Ecy WSU	45WR23.6	-120.6492	47.5988	Wenatchee RM 23.6	A	19.3		19.8	above class A
Ecy WSU	45WR33.0	-120.7231	47.6493	Wenatchee RM33.0	AA	19.3		19.9	
USFS	45PC10.9	-120.6636	47.4430	Peshastin RM10.9	A	19.1		20.0	
Ecy SHU	45B050	-120.6613	47.5791	Icicle RM0.2	A	19.1		20.0	
Ecy WSU	45WR46.4	-120.6609	47.7672	Wenatchee RM46.4	AA	19.0		19.4	
Ecy SHU	45J070	-120.7155	47.8008	Nason RM0.8	AA	18.9		19.7	
Ecy WSU	45WR30.3	-120.7171	47.6090	Wenatchee RM30.3	AA	18.9		19.4	
Ecy WSU	45WR53.9	-120.7230	47.8086	Wenatchee RM53.9	AA	18.9		20.4	
USFS	45NC03.8	-120.7291	47.7660	Nason RM3.8	AA	18.9		19.6	
USFS	45WR28.1	-120.7018	47.5843	Wenatchee RM28.1	AA	18.6		19.1	
Ecy WSU	45BR00.1	-120.4759	47.5214	Brender RM0.1	A	18.5		19.0	
Ecy SHU	45A240	-120.7141	47.8099	Wenatchee RM53.5	AA	18.0		18.9	
Ecy WSU	45CD00.1	-120.6744	47.5768	Cascade Orchard ditch	A	17.8		21.3	
USFS	45MCEF	-120.4979	47.3938	Mission (East Fork)	A	17.6		18.6	
USFS	45MC12.7	-120.5108	47.3687	Devils Gulch	A	17.4		18.1	
Ecy WSU	45IC02.3	-120.6667	47.5636	Icicle RM02.3	A	17.4		18.4	
Ecy WSU	45IC05.9	-120.7147	47.5435	Icicle RM05.9	AA	17.1		17.9	
USFS	45IC05.6	-120.7069	47.5439	Icicle RM05.6	AA	16.9	above core	17.6	
Ecy WSU	45CW00.5	-120.6495	47.7884	Chiwawa RM0.5	AA	16.6		17.3	above class AA
Ecy WSU	45IC11.4	-120.7908	47.5732	Icicle RM11.4	AA	16.4		17.3	
Ecy WSU	45IC09.9	-120.7819	47.5628	Icicle RM09.9	AA	16.3		16.8	
Ecy WSU	45BC00.1	-120.6608	47.7670	Beaver RM0.1	AA	15.8		16.8	
Ecy WSU	45CS00.3	-120.6476	47.6053	Chumstick RM0.3	A	15.4		15.9	
Ecy WSU	45IC23.4	-120.9081	47.6086	Icicle RM23.4	AA	15.4		16.1	
Ecy WSU	45IC15.0	-120.8485	47.6072	Icicle RM15.0	AA	15.4		16.1	
USFS	45PC09.3	-120.6593	47.4608	Peshastin RM9.3	AA	14.8		15.3	
USFS	45IN00.7	-120.6733	47.4619	Ingalls RM0.7	AA	14.6		15.2	
Ecy WSU	45EC00.1	-120.7747	47.5547	Eightmile RM0.1	AA	14.4		15.1	
Ecy WSU	45JC00.1	-120.9074	47.6085	Jack RM0.1	AA	14.2		14.9	
USFS	45BCSF	-120.5960	47.7692	Beaver (South Fork)	AA	14.2		14.9	
Ecy SHU	45G060	-120.7288	47.6796	Chiwaukum RM0.2	AA	13.8		14.6	
Ecy WSU	45EC02.7	-120.8139	47.5360	Eightmile RM2.7	AA	13.6		15.9	
USFS	45CH00.8	-120.7354	47.6873	Chiwaukum RM0.8	AA	13.5		14.3	
Ecy WSU	45MT00.1	-120.8134	47.5342	Mountaineer RM0.1	AA	12.8		13.9	
USFS	45BCNF	-120.5927	47.7819	Beaver (North Fork)	AA	12.3		12.9	

1) Agency abbreviations:
Ecy WSU: Department of Ecology, Watershed Studies Unit
Ecy SHU: Department of Ecology, Stream Hydrology Unit
USFS: United States Forest Service

Table 5. Summary of maximum water temperatures in the Wenatchee basin during 2003.

Agency (1)	Station	Longitude (decimal degrees)	Latitude (decimal degrees)	Description	Water Quality Class	Highest 7 day average daily maximum water temperature during 2003 (deg C)		Highest daily maximum water temperature during 2003 (deg C)	
NPSU	45MC02.2	-120.47681	47.49561	Mission at Woodring	A	26.5		29.9	
NPSU	45PC00.3	-120.58062	47.55719	Peshastin Cr near mouth	A	24.5		25.5	
NPSU	45MC01.2	-120.47332	47.50981	Mission Cr at Binde	A	24.0		25.7	
NPSU	45NC00.7	-120.7154	47.8006	Nason at Cedar Brae	AA	22.0		22.8	
USFS	45NC00.3	-120.7446	47.8382	Across from milepost 4 on HWY 207	AA	21.9		22.7	
NPSU	45NC06.0	-120.76042	47.76747	Nason abv Kahler	AA	21.6		22.2	
NPSU	45MC00.5	-120.47114	47.51707	Mission at Pioneer	A	21.6		24.1	
NPSU	45NC04.7	-120.74153	47.76064	Nason at Cole's Corner	AA	21.4		22.0	
USFS	45PC11.0	-120.6558	47.4455	100' upstream of Negro Creek conf	AA	21.3		21.8	
NPSU	45PC03.6	-120.62357	47.52722	Peshastin below Larse	A	21.1		21.8	
NPSU	45MC00.1	-120.4748	47.5213	Mission at Sunset	A	20.8		22.5	
NPSU	45PC14.9	-120.65487	47.39659	Peshastin Cr headwater	AA	20.6		21.1	
NPSU, WSU	45YC00.1	-120.4749	47.49944	Yaksum Cr at road crossing	A	20.6		21.5	
NPSU	45PC12.4	-120.65649	47.42804	Peshastin below Culve	AA	20.5		21.0	
NPSU	45MC04.5	-120.49053	47.46968	Mission Cr above bridge	A	20.4		21.2	
NPSU	45MC07.6	-120.50249	47.43373	Mission below Sand Cr	AA	20.1		20.6	
NPSU, AMU, WSU	45NN0.2	-120.47609	47.52144	Noname Cr at Mill Road	A	20.0		20.4	above class A
NPSU, AMU, WSU	45BR00.1	-120.47564	47.52157	Brender at Sunset	A	19.1	above non-core	19.6	
NPSU	45TC00.1	-120.6501	47.3975	Tronsen Cr near mouth	AA	19.0		19.8	
USFS	45MC09.2	-120.5081	47.4282	Just below bridge on staff gauge	AA	18.9		19.5	
NPSU	45MC09.3	-120.5092	47.4171	Mission at NF gage	AA	18.9		19.5	
NPSU	45CS09.1	-120.63252	47.71691	Chumstick above Lil C	A	18.9		20.5	
NPSU	45PC06.5	-120.6363	47.4925	Peshastin above Camas	A	18.7		19.3	
NPSU	45CS06.1	-120.63972	47.67942	Chumstick below Clark	A	18.6		20.9	
NPSU	45NC11.2	-120.83636	47.7788	Nason above Gill Cr	AA	18.4		19.0	
NPSU	45NC19.2	-120.96669	47.77392	Nason at Berne facility	AA	18.4		18.9	
USFS	45MC11.0	-120.5081	47.399	Immediately downstream of 2nd bridge	AA	18.2		18.6	
NPSU	45NC13.9	-120.87497	47.78331	Nason above Mahar	AA	18.0		18.8	
NPSU	45NC16.3	-120.91718	47.77514	Nason above Whitepine	AA	17.9		18.4	
SHU, NPSU, USFS	45PC09.3	-120.6596	47.46301	Peshastin above Ingalls	AA	17.9		18.4	
NPSU	45RC00.0	-120.8065	47.7685	Roaring/Coulter Cr	AA	17.8		21.1	
NPSU	45LC00.0	-120.62382	47.52207	Larsen Cr near mouth	A	17.8		18.6	
NPSU	45NC23.6	-121.03686	47.78461	Nason below 6700 rd	AA	17.6		18.1	
USFS	45SN00.3	-120.5081	47.4282	Sand Creek at mouth	A	17.5		18.1	
NPSU	45SE00.1	-120.61394	47.71662	Second Cr at Merry	A	16.8		17.4	
SHU, NPSU	45PC08.4	-120.65611	47.4749	Peshastin below Ingalls	AA	16.7	above core	17.3	
NPSU	45MP00.0	-120.63197	47.51116	Mill Cr near mouth	AA	16.6		17.3	
USFS	45PC09.1	-120.6558	47.4599	Below junction with Ingalls Creek	AA	16.4		17.1	above class AA
NPSU	45IN00.6	-120.6717	47.463	Ingalls Cr at road crossing	AA	15.6		16.1	
USFS	45IN00.7	-120.6778	47.4599	50' downstream of bridge at Ingalls	AA	15.6		16.1	
NPSU	45NC26.3	-121.07581	47.77369	Nason below Stevens C	AA	14.6		15.3	
NPSU	45WP00.1	-120.9156	47.7746	Whitepine Cr near mouth	AA	14.4		15.1	
NPSU	45NG00.0	-120.6613	47.44369	Negro Cr mouth	AA	14.0		14.4	
NPSU	45MN00.1	-121.01049	47.77616	Mill Cr mouth Nason	AA	13.9		14.3	
NPSU	45RB00.0	-120.652	47.4488	Ruby Cr near mouth	AA	13.8		14.1	

1) Agency abbreviations:
Ecy NPSU: Department of Ecology, Non Point Studies Unit
Ecy WSU: Department of Ecology, Watershed Studies Unit
Ecy SHU: Department of Ecology, Stream Hydrology Unit
USFS: United States Forest Service

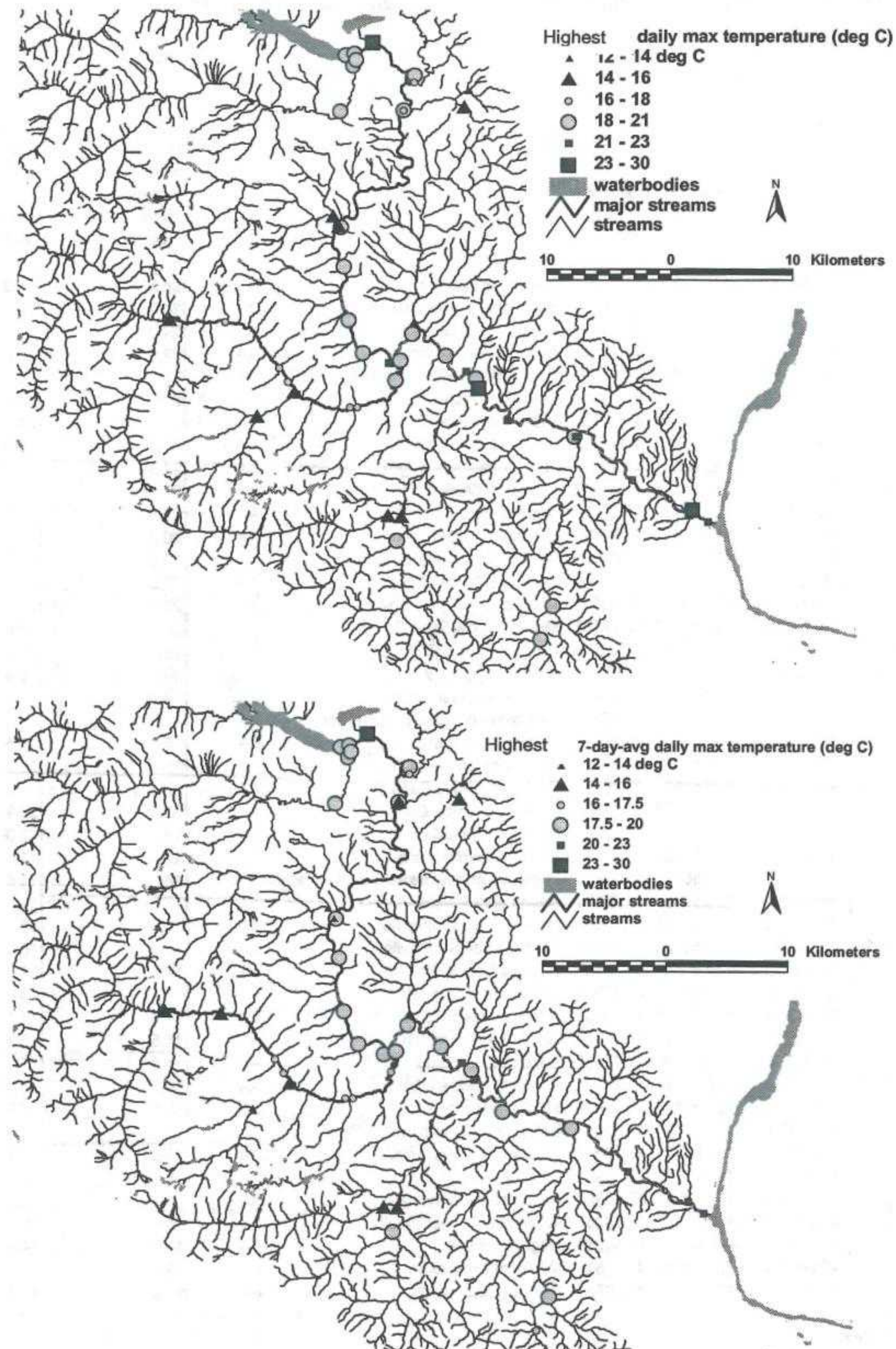


Figure 11. The highest daily maximum (upper map) and highest 7-day averages of daily maximum (lower map) water temperatures in the Wenatchee River and its tributaries during 2002.

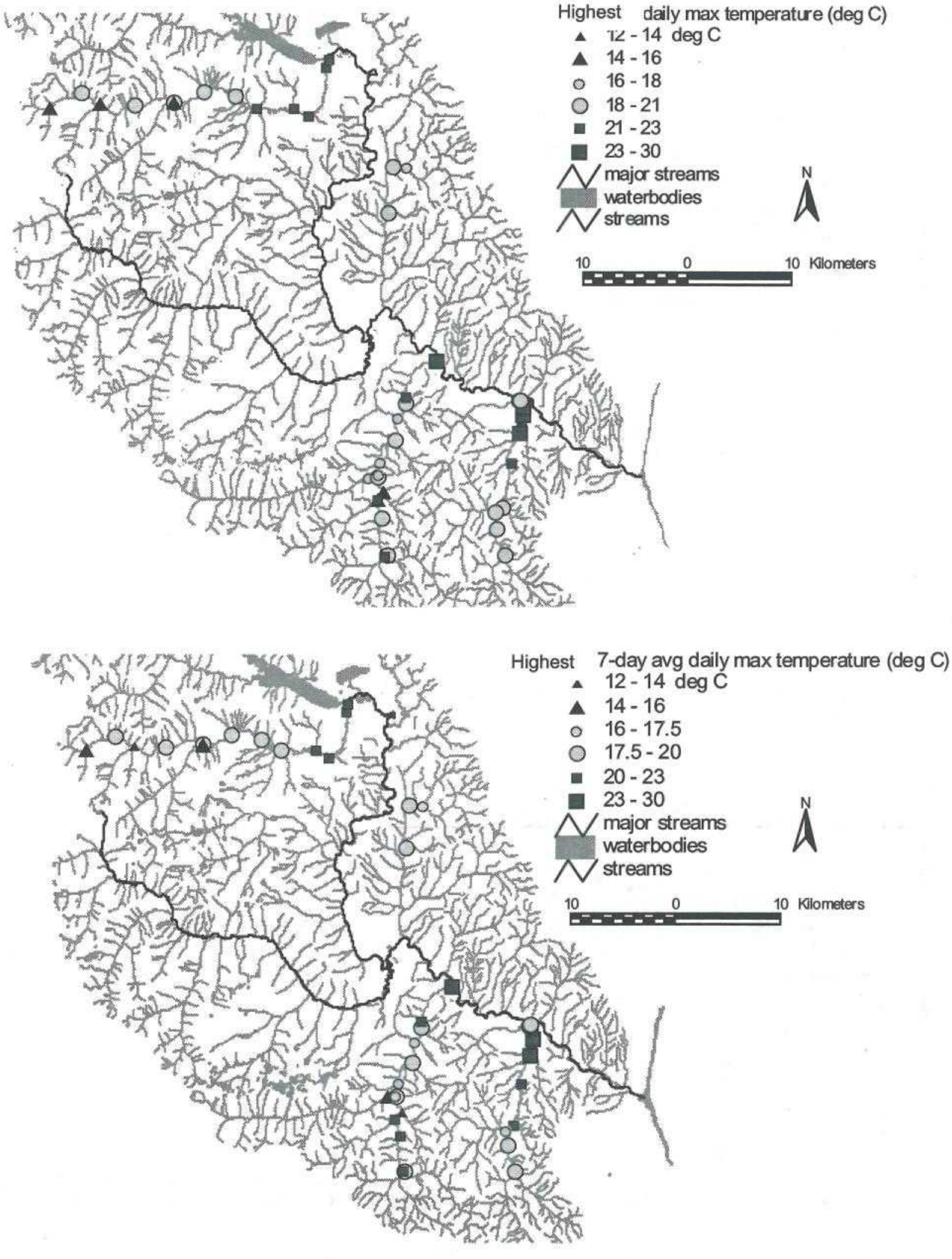
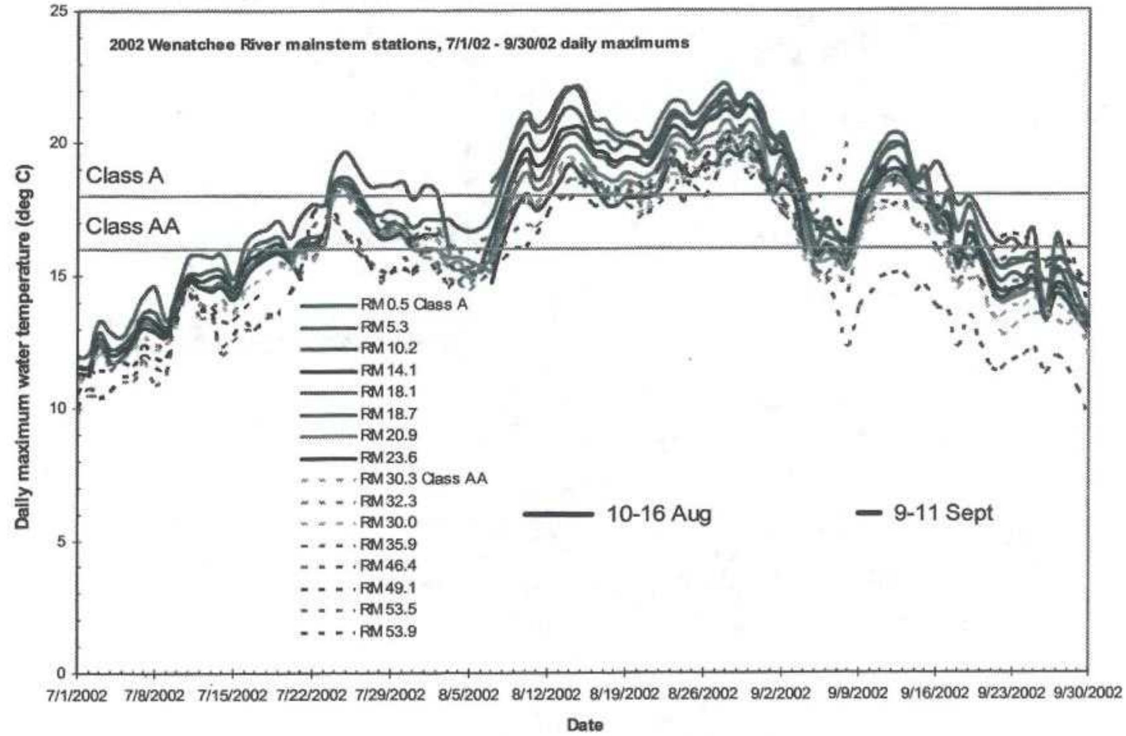


Figure 12. The highest daily maximum (upper map) and highest 7-day averages of daily maximum (lower map) water temperatures in the Wenatchee River and its tributaries during 2003.



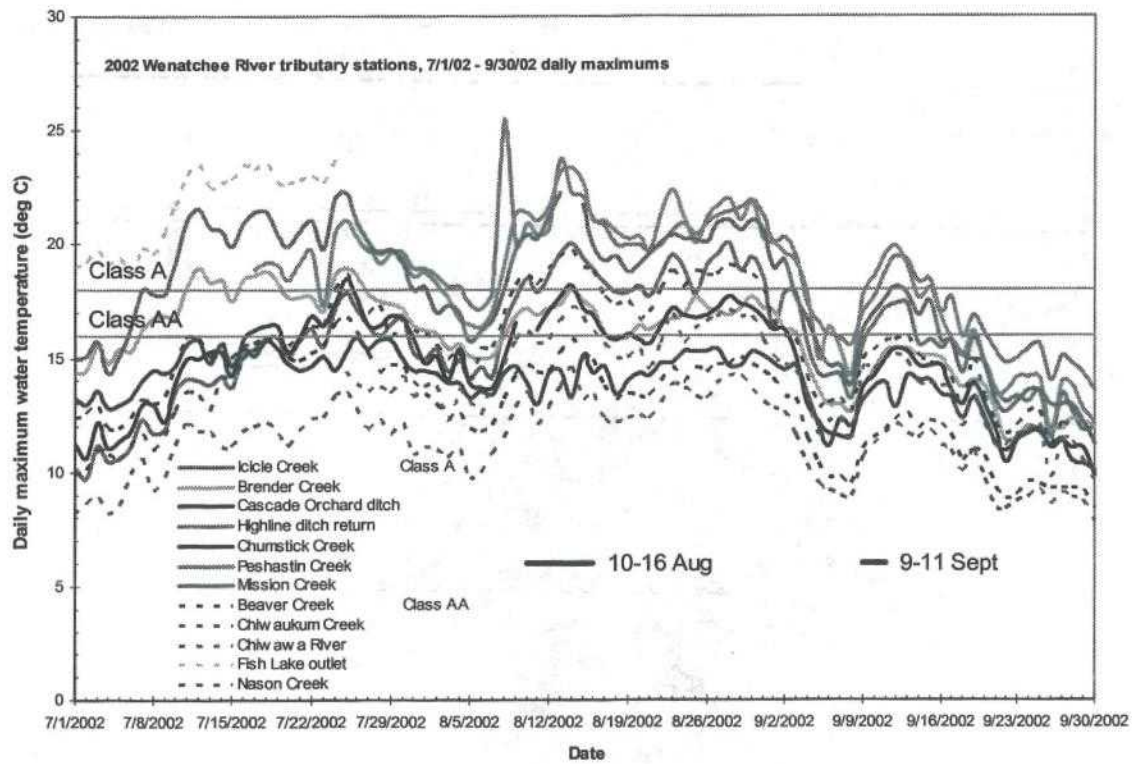
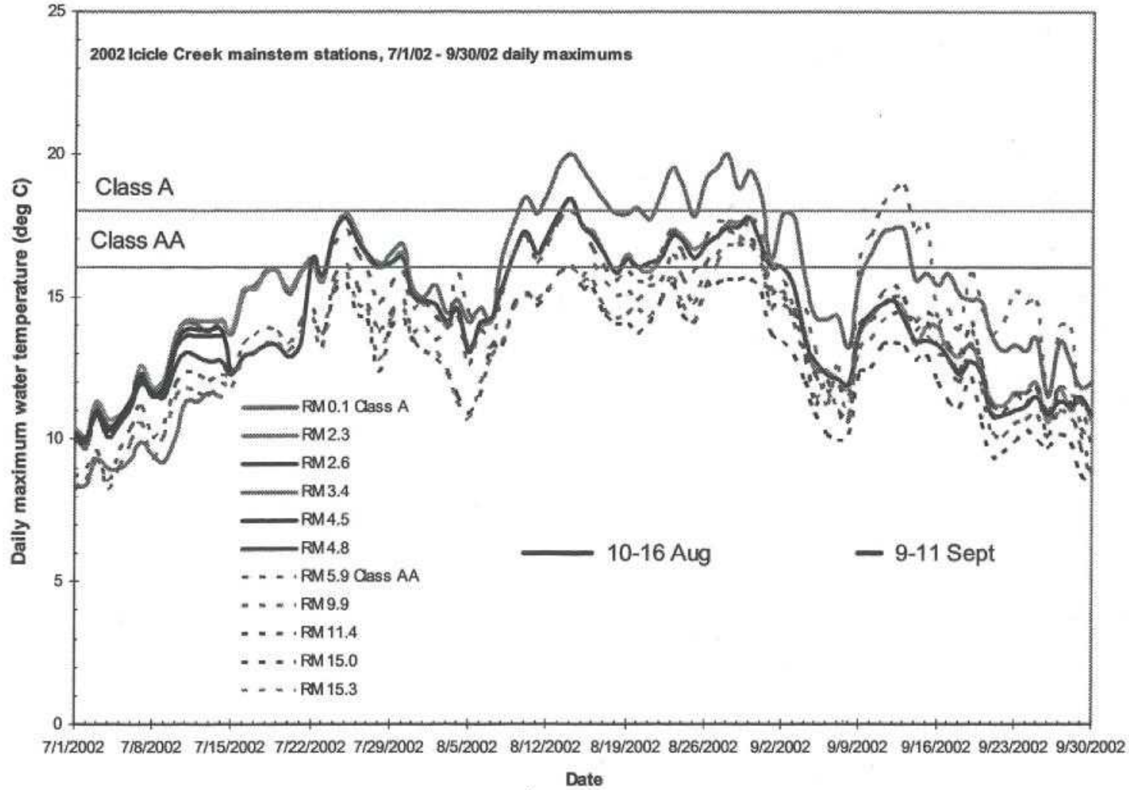


Figure 13. Daily maximum water temperatures in the mainstem Wenatchee River and its tributaries from July to September 2002.



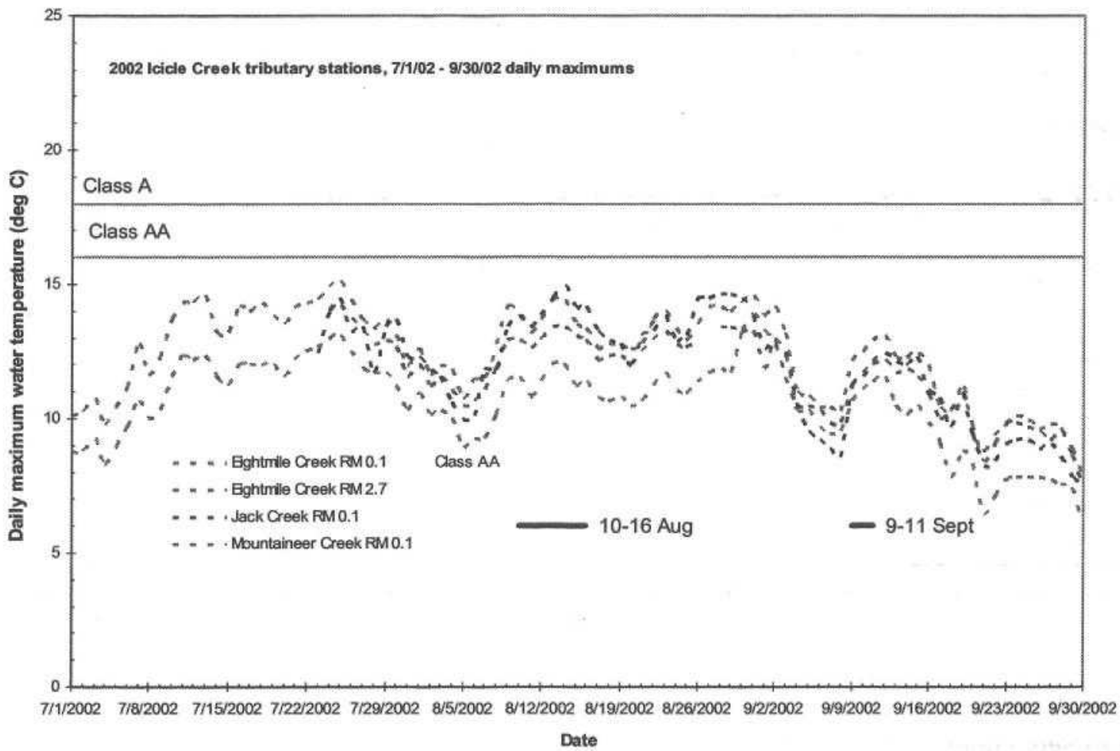
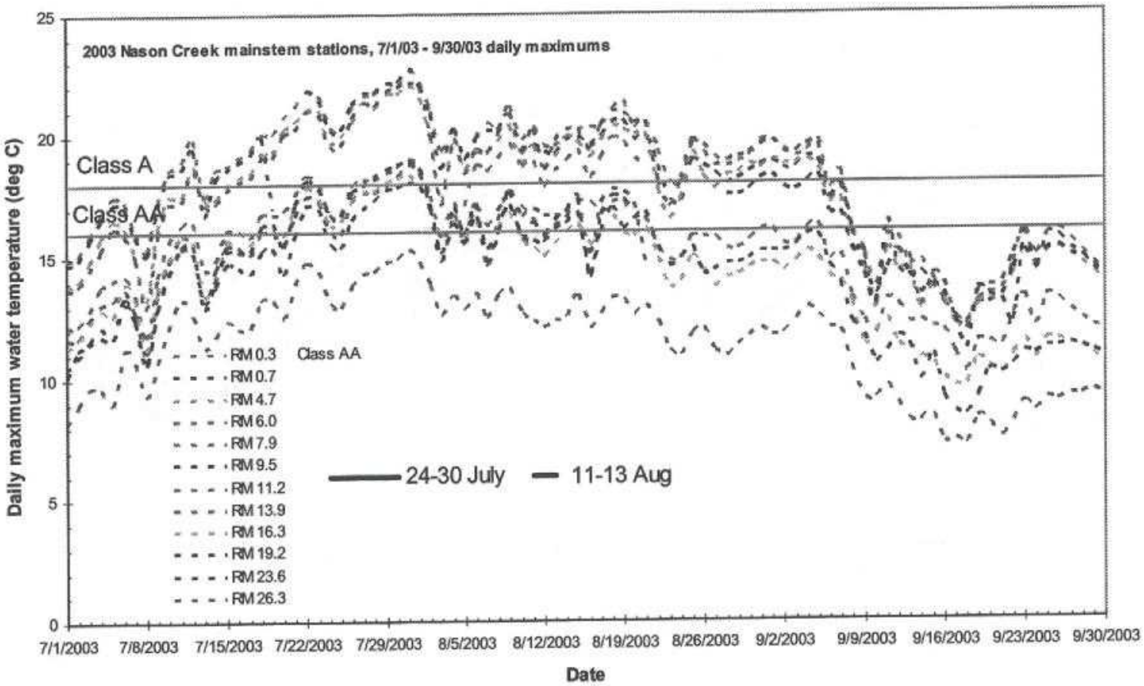


Figure 14. Daily maximum water temperatures in the mainstem Icicle Creek and its tributaries from July to September 2002.



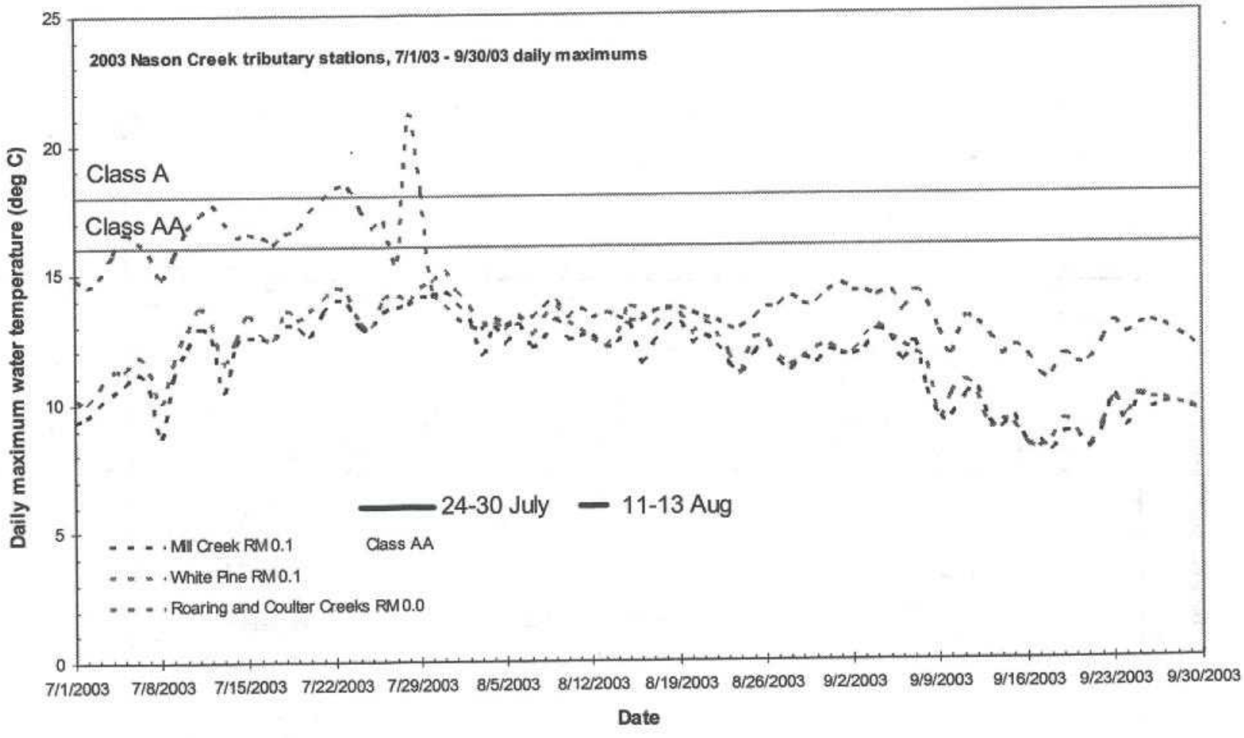
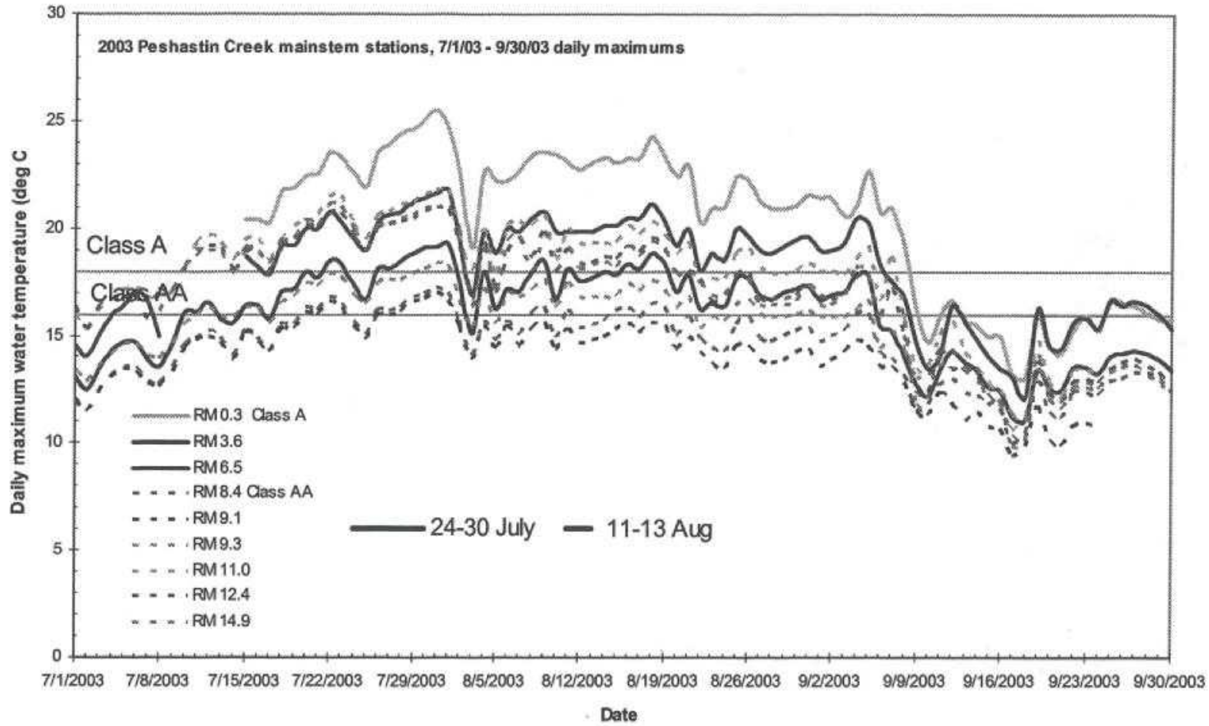


Figure 15. Daily maximum water temperatures in the mainstem Nason Creek and its tributaries from July to September 2003.



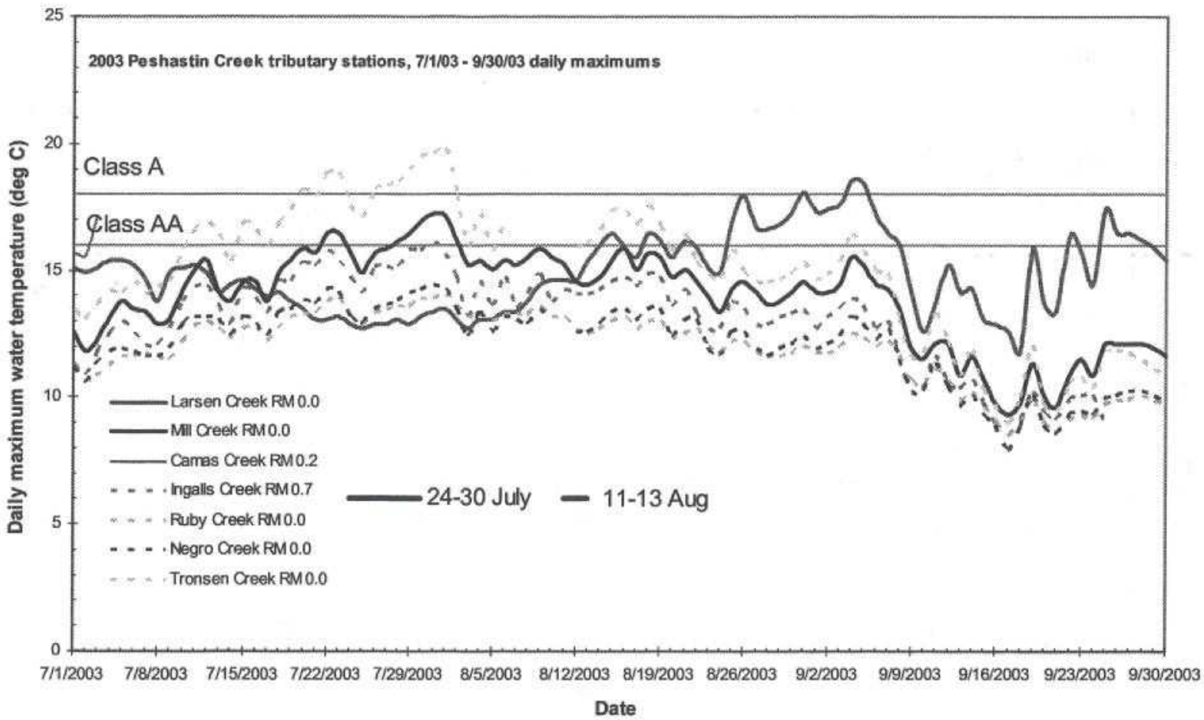
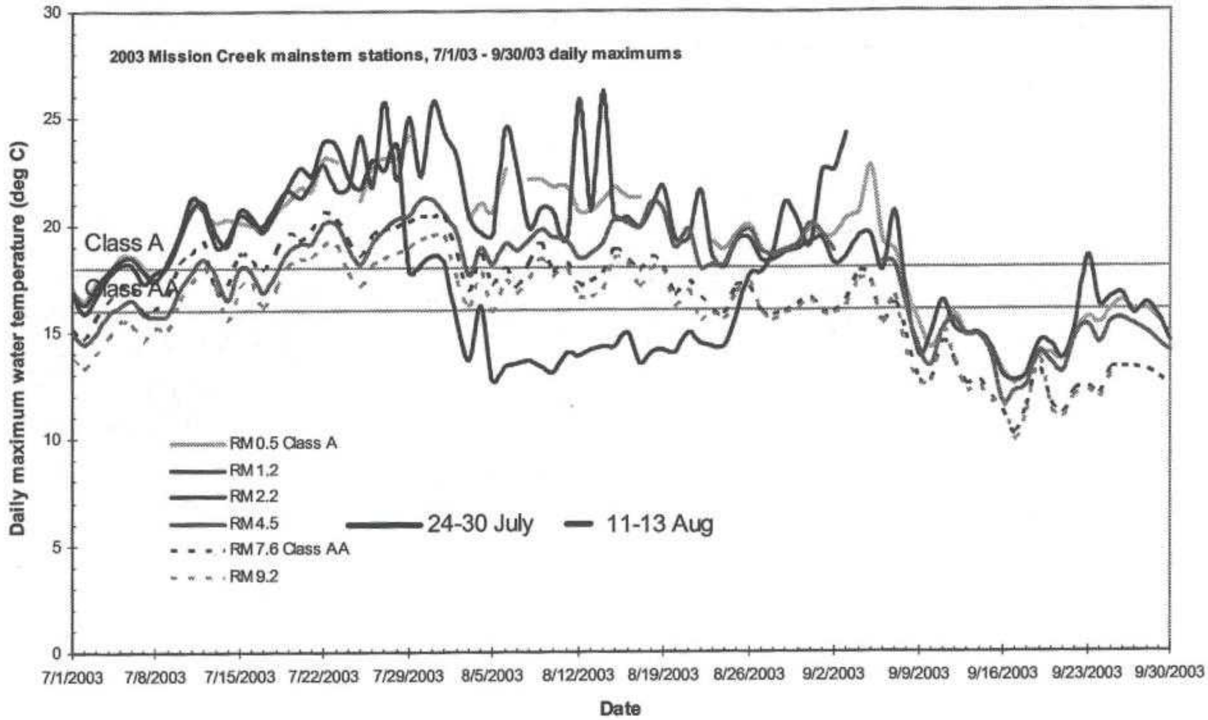


Figure 16. Daily maximum water temperatures in the mainstem Peshastin Creek and its tributaries from July to September 2003.



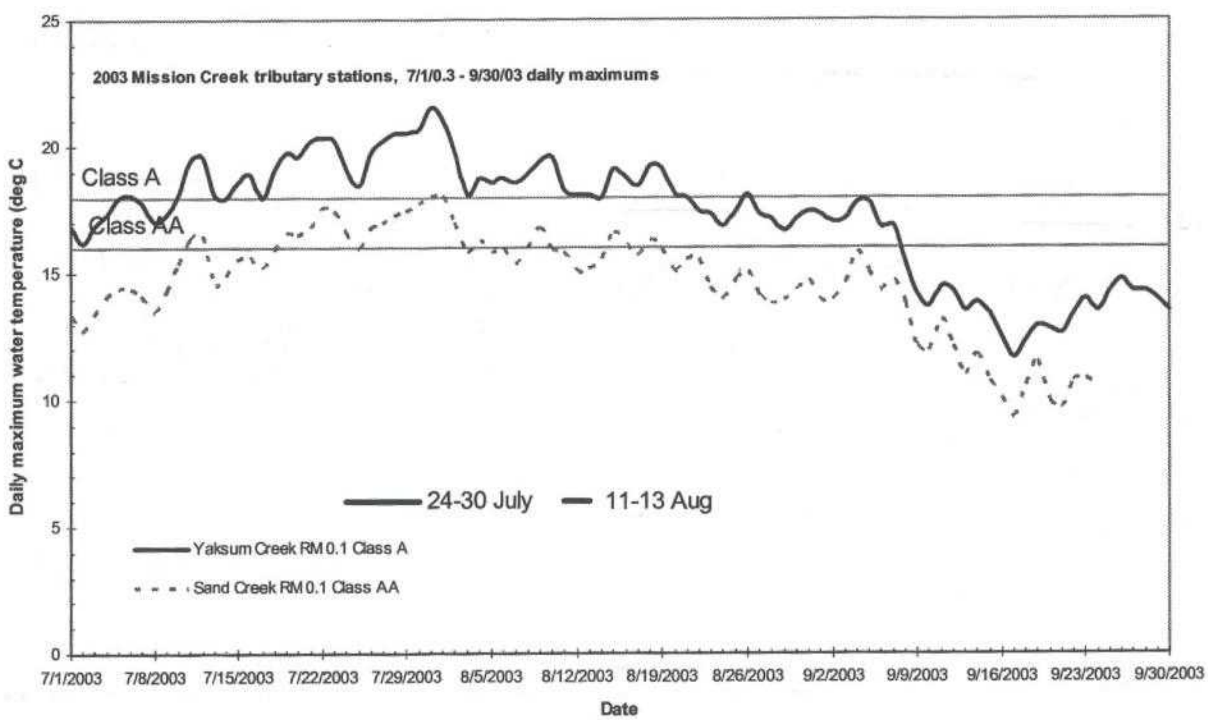


Figure 17. Daily maximum water temperatures in the mainstem Mission Creek and its tributaries from July to September 2003.

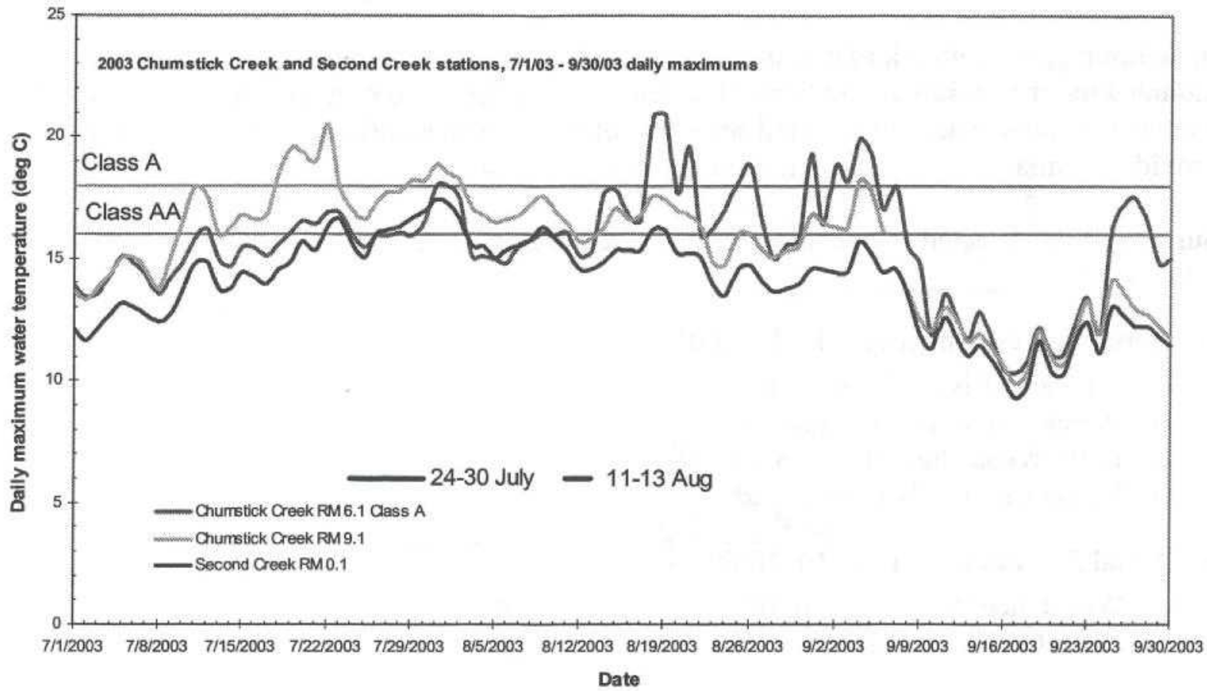


Figure 18. Daily maximum water temperatures in Chumstick Creek and Second Creek from July to September 2003.

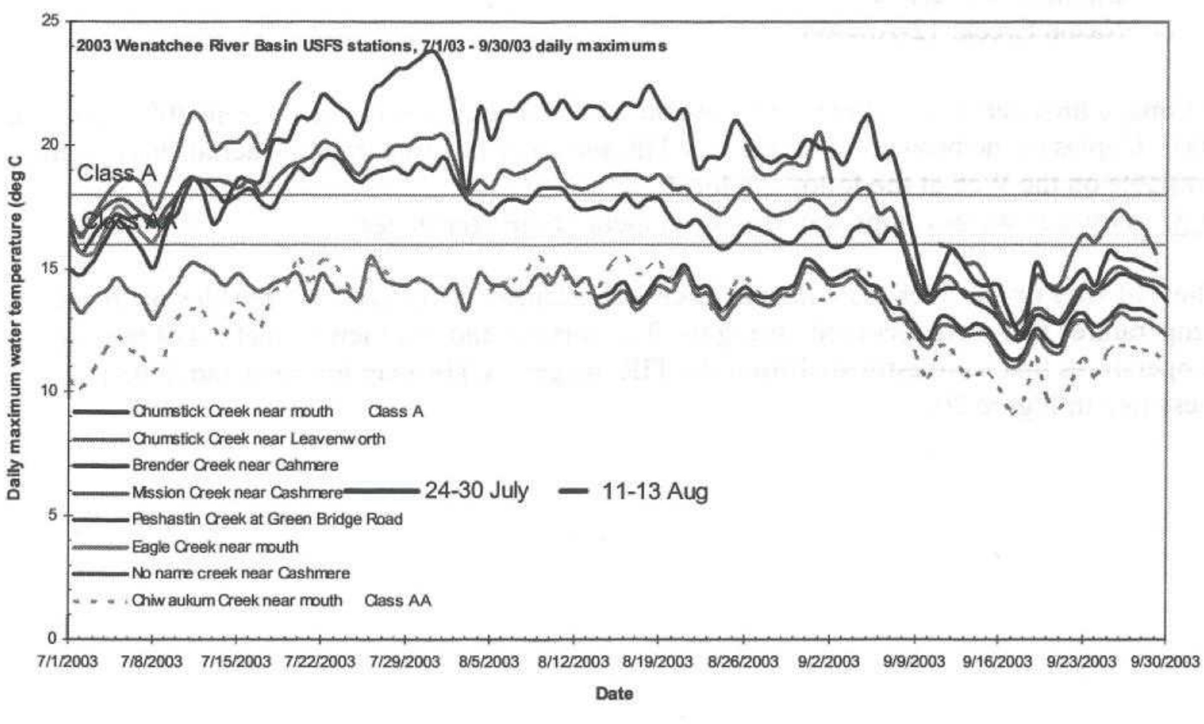


Figure 19. Daily maximum water temperatures at USFS stations in the Wenatchee River basin from July to September 2003.

Water temperature data – aerial surveys

In addition to the network of continuously recording temperature dataloggers, a helicopter-mounted thermal infrared radiation (TIR) sensor and color video camera was used to take TIR and visible color images of selected segments of the streams and rivers in the watershed to provide a spatially continuous image of surface temperature.

Surveys of the selected segments were conducted during August of 2001, 2002, and 2003 as follows:

- Aerial Surveys on August 12-14, 2001:
  - Chiwawa River, 12-Aug-01
  - Wenatchee River, 13-Aug-01
  - Little Wenatchee River, 13-Aug-01
  - Nason Creek, 14-Aug-01
- Aerial Surveys on August 16, 2002:
  - Wenatchee River, 16-Aug-02
  - Icicle Creek, 16-Aug-02
- Aerial Surveys on August 11-12, 2003:
  - Mission Creek, 11-Aug-03
  - Brender Creek, 11-Aug-03
  - Peshastin Creek, 11-Aug-03
  - Chumstick Creek, 11-Aug-03
  - Nason Creek, 12-Aug-03

An image browser was developed to view the TIR and color video images from 2001, 2002, and 2003. Copies of the browser software and TIR and color imagery from the aerial surveys are available on the Web at the following location:
http://www.ecy.wa.gov/apps/watersheds/temperature/tir/wenatchee/

The TIR files on the Web also include Excel spreadsheets of longitudinal profiles of stream temperatures that were recorded during the TIR surveys and ArcView shapefiles of the water temperatures that were estimated from the TIR images. A TIR map for 2002 and 2003 is presented in Figure 20.

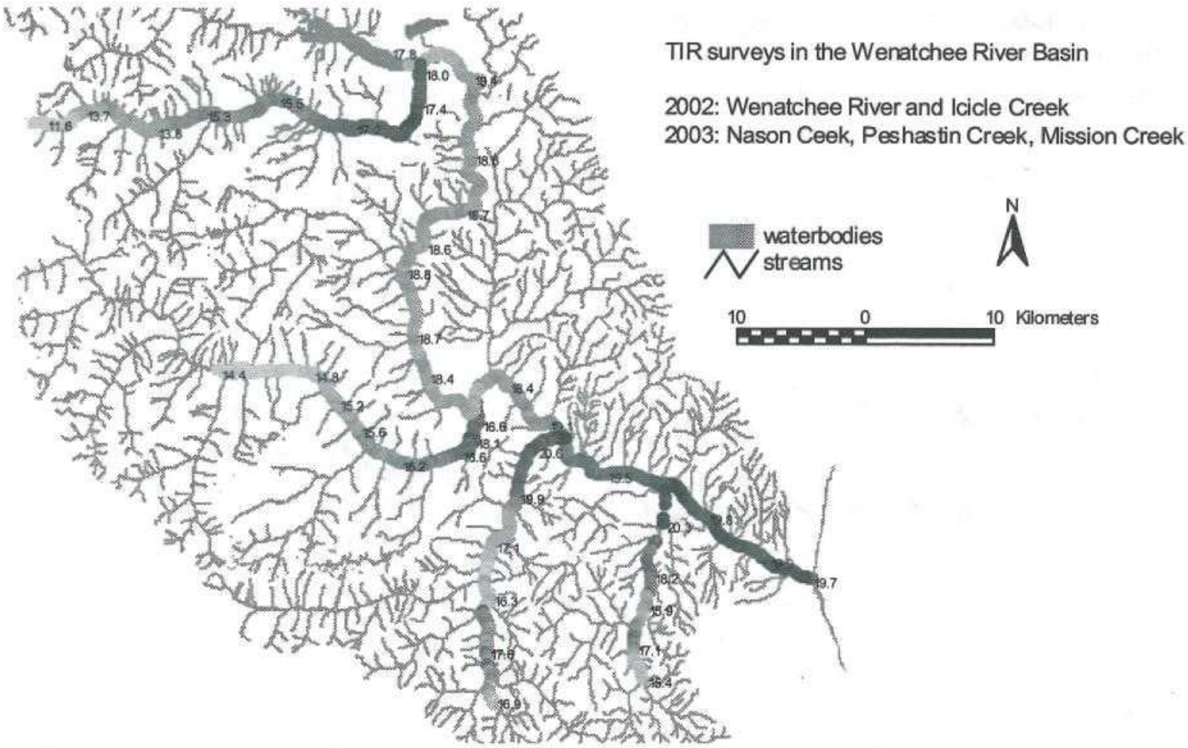


Figure 20. TIR surveys in the Wenatchee River basin in 2002 and 2003.

Wenatchee Lake temperatures strongly influence the Wenatchee River temperature longitudinal profile in the upper watershed. As an example, Figure 21 shows two temperature profiles on two different years. The 2001 condition corresponds to a hot period and close to 7Q10 flows, while the 2002 profile is closer to a median meteorological and flow condition.

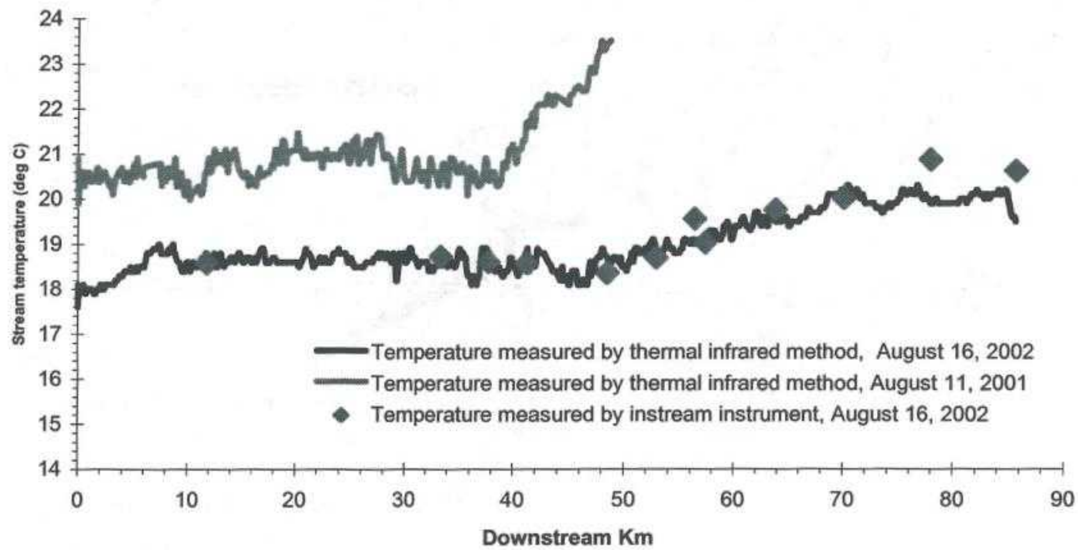


Figure 21. Wenatchee River temperature longitudinal profiles on August 16, 2002 and August 11, 2001.

Streamflow data

Continuous streamflows were recorded in the Wenatchee River watershed as described by Bilhimer et al, 2002. The continuous flow measurements can be browsed or downloaded from the Web at the following location:
https://fortress.wa.gov/ecy/wrx/wrx/flows/regions/state.asp?region=3

Figure 22 shows the current USGS gaging stations and the Ecology 2002 and 2003 flow stations.

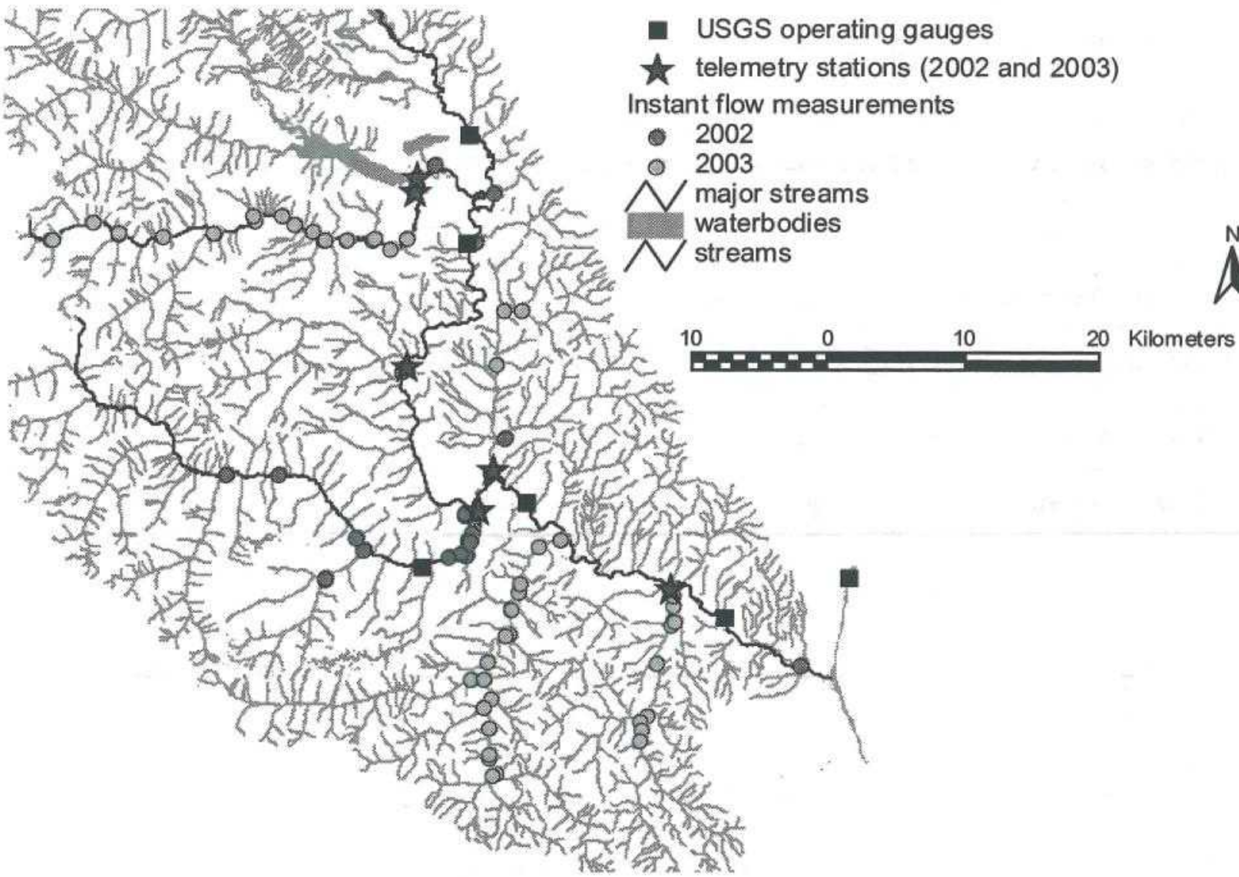


Figure 22. Ecology and USGS flow measurement stations in the Wenatchee River basin in 2002 and 2003.

USGS stations with greater than 10 years of flow data were used to estimate the 7-day consecutive low flow with a 10-year return frequency (7Q10) and the 7-day consecutive low flow with a 2-year return frequency (7Q2) during July-August. Low flow statistics were estimated using a 3-parameter log normal distribution (Table 6).

Table 6. Low flow statistics for July-August at USGS gaging stations in the Wenatchee River basin.

Station	Station name	Drainage area (sq mi)	Period of record	7Q2 (cfs)	7Q10 (cfs)	Years of data
12456500	Chiwawa River near Plain	170	1911-1914 1936-1949 1954-1957 1991-present	169	108	33
12458000	Icicle Creek above Snow Creek	193	1936-1971 1993-present	160	117	45
12461400	Mission Creek above Sand Creek	39.8	1958-1971	2.4	1.7	14
12455000	Wenatchee River below Lake Wenatchee	273	1932-1958	405	272	27
12457000	Wenatchee River at Plain	591	1910-1979 1989-present	747	471	81
12459000	Wenatchee River at Peshastin	1,000	1929-present	857	556	74
12462500	Wenatchee River at Monitor	1,301	1962-present	809	479	40

Climate data

Meteorological data relevant to the Wenatchee River basin water temperature assessment were obtained from various weather data sources (Figure 23):

- The state Department of Transportation (DOT) operates and maintains weather stations at four locations in WRIA 45: Dryden Road, Cashmere, Stevens Pass, and Blewett Pass.
- At Pangborn Airport in Wenatchee, surface weather data are recorded by the National Weather Service in METAR format (the international code to report routine, hourly weather conditions at air terminals).
- NOAA's National Climate Data Center (NCDC) operates several weather stations in the Wenatchee watershed.
- Washington State University operates a Public Agricultural Weather System (PAWS) weather station at the Tree Forest Research and Extension Center (TFREC) in Wenatchee.
- Ecology recorded relative humidity and air temperature measurements at several instream datalogger locations during the monitoring period.

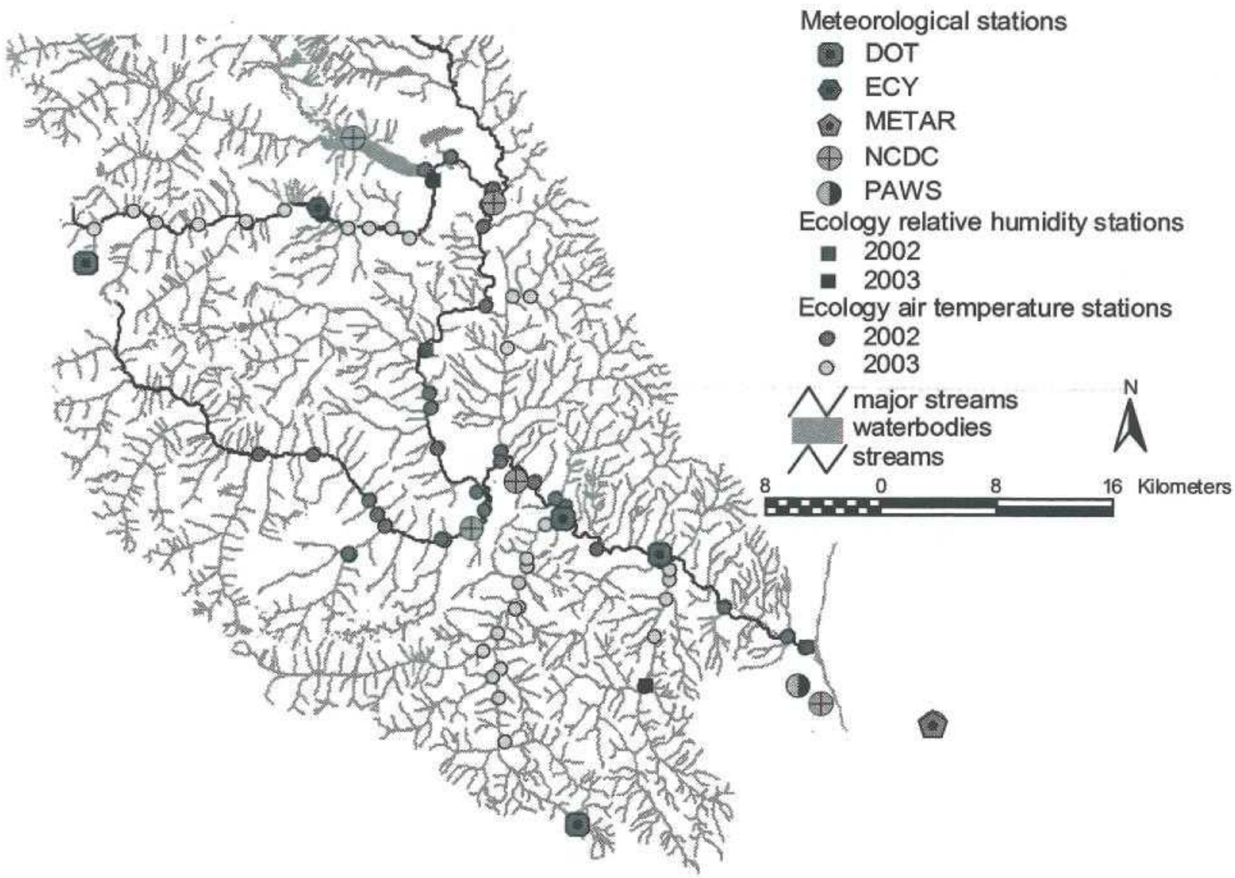


Figure 23. Meteorological stations relevant for the Wenatchee River basin. Ecology relative humidity and air temperature stations in 2002 and 2003.

The NOAA-COOP (National Oceanic and Atmospheric Administration - Cooperative Observer Program) meteorological station at Leavenworth was investigated for long-term statistics due to the availability of historical meteorological data and to the representative position in the basin of this station for the studied area. The highest daily mean air temperature and the highest 7-day average of daily mean air temperature were selected for each year and were used to determine the median and the 90th percentile conditions. Forty-nine years of data were used for this statistical analysis summarized in Table 7.

Table 7. Estimated daily maximum and minimum air temperatures on weeks and days with the highest daily mean air temperatures for a median year and 90th percentile year at the NOAA-COOP station in Leavenworth (°C; 49 years of data).

Daily temperature	Median year		90th percentile year	
	Hottest week, 8/8-14/2001	Hottest day, 7/22/2000	Hottest week, 8/11-17/2001	Hottest day, 7/23/1994
Mean	24.8	27.2	26.2	28.9
Maximum	36.6	36.7	37.8	41.1
Minimum	13.2	17.8	14.5	16.7

A regression of average daily maximum and minimum air temperatures during July – August versus elevation along the streams in the Wenatchee River basin is presented in Figure 24 with data from www.daymet.org. Daymet data is a model that uses a digital elevation model and daily observations of minimum and maximum temperatures to generate an 18-year daily data set (1980-1997) of temperatures as a continuous surface at a 1 Km resolution.

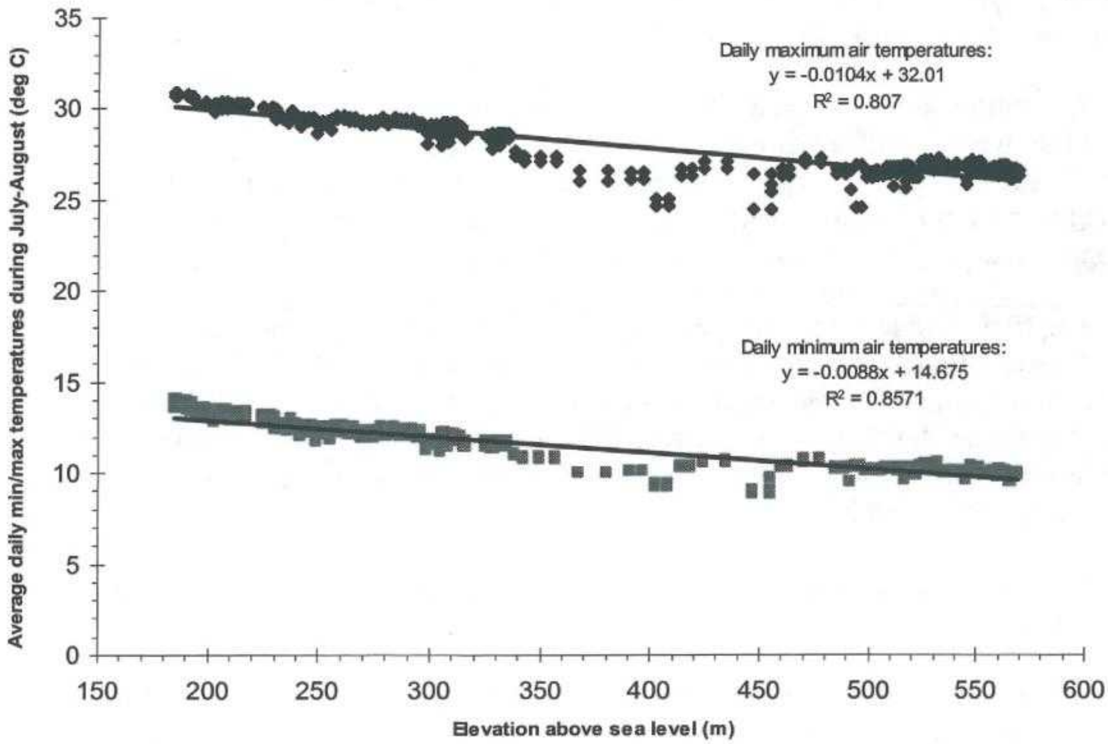


Figure 24. Regression of average daily maximum and minimum air temperatures versus elevation along the streams in the Wenatchee River basin.

Riparian vegetation and effective shade

Mapping the near-stream vegetation cover at current conditions

Near-stream vegetation cover, along with channel morphology and stream hydrology, represent the most important factors that influence stream temperature. To obtain a detailed description of the existing riparian conditions in the Wenatchee River basin, a combination of GIS analysis and aerial photography interpretation was used.

A 300-foot buffer from each bank of the Wenatchee River (Figure 25) was defined along both sides of the river in a GIS environment. Vegetation polygons were mapped at a 1:2500 scale within the stream buffer. A vegetation type code that combines information about the average tree height and canopy density was assigned to each delineated polygon using full-color digital orthophoto quadrangles (DOQs) 1:24000, as represented in Figure 25.

To increase the accuracy of the image interpretation (riparian vegetation type, height, and density), an additional set of aerial photographs was used: digital photographs acquired during the TIR survey. These photos (about 1800 images with about 40% overlap) were taken from low altitude (approximately 300 m) and provided a higher level of detail than the orthophotos. The images are more accurate, and specific details such as tree shadows helped in deciphering the species composition and height.

Field observations of vegetation type, height, and density were also compared against the digitized GIS data.

The near-stream vegetation cover for the Wenatchee River tributaries was mapped using the ArcView GIS dynamic segmentation method which proved to be more cost-effective and sufficiently accurate compared to the polygon delineation method (Cristea, 2004).

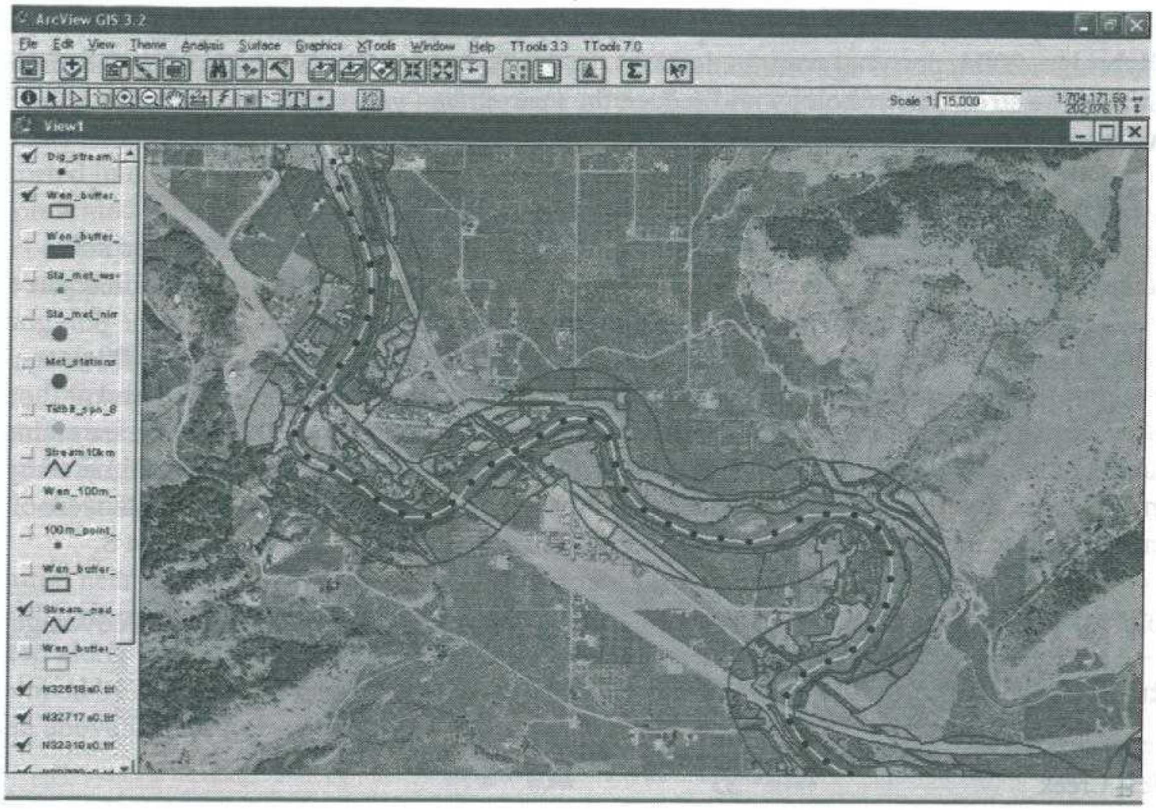


Figure 25. Example of the digital orthophoto quad (DOQ) for the Wenatchee River and digitized channel geometry and vegetation polygons.

Potential near-stream vegetation cover

The height and density of site potential riparian vegetation (at mature stages) were estimated based on various GIS existing coverages and expert opinions, as described below.

The lower reaches of the Wenatchee River (RM 27.1 – confluence with the Columbia River) are located in a semi-arid area where the near-stream vegetation is dominated by shrubs and small trees. Scattered tall trees can also be seen along the banks. At mature stages, riparian shrubs can reach an average height of less than 10 m. Counting the grasses and shrubs, an average density of about 55% and an average tree height of about 10 m are estimated (Lillybridge, 2004, personal communication). High trees, such as the black cottonwood, can grow as high as 35 – 40m and have an average canopy density of about 20% (Lillybridge, 2004, personal communication). Patches of orchard areas, barren areas, and developed areas complete the near-stream riparian vegetation mosaic in the lower reaches of the Wenatchee River.

The near-stream vegetation patterns in the upper reaches of the Wenatchee River (RM 27.1 – Lake Wenatchee) are different than those described for the lower reaches. The upper part of the river is located in a forested area belonging to Wenatchee National Forest. Average annual precipitation values are higher in the upper basin at higher elevations and can sustain denser and taller vegetation. Average near-stream tree communities (grasses and shrubs not taken into account) are estimated at about 60-70% canopy cover and 25 m average tree height (Lillybridge, 2004, personal communication). In the Tumwater Canyon, bedrock outcrops dominate the stream morphology and reduce the near-stream vegetation density. Along this reach, most of the stream shading is provided by topography.

Washington State Department of Natural Resources (DNR) soils coverage (http://www3.wadnr.gov/dnrapp6/dataweb/dmmatrix.html#Soils) provides digitized soils delineations and soil attributes. Site index data – a designation of the quality of a forest site based on the height of the dominant and co-dominant tallest trees in a stand – is one of the polygon attributes in the DNR soils coverage. Usually, the age of the trees chosen is 50 or 100 years. For example, if the average height attained by the tallest trees in a fully stocked stand at the age of 50 years is 75 feet, the site index is 75 feet. Western Washington site conditions are estimated by using an index age of 50 years, while eastern Washington site conditions are estimated by using an index age of 100 years. Tree heights for the tallest trees from the DNR data were summarized for the investigated streams in the Wenatchee River as shown in Table 8.

Table 8. Maximum tree heights in the Wenatchee River basin (from the DNR soils coverage).

Waterbody	Tree height (m)
Wenatchee River*	34
Icicle Creek	33
Nason Creek	32
Peshastin Creek	30
Mission Creek	28
Average for the whole basin	31.5

* RM 27.1 to headwaters, for the available GIS data

The Interagency Vegetation Mapping Program (IVMP) provides maps of existing vegetation for all lands in the Northwest Forest Plan area within Oregon and Washington consistent with the Interagency Vegetation Strike Team Standards. The participating agencies in the IVMP are the Bureau of Reclamation, OR/WA State Office, USFS Region 6 and the Pacific Northwest Research Station. The IVMP GIS data are available on the Internet at: http://www.or.blm.gov/gis/projects/ivmp.asp . The IVMP provides GIS coverages for tree sizes and canopy densities.

The grids created for eastern Washington were developed in the IVMP project using a combination of image classification techniques and regression analysis. Through regression modeling, a relationship is derived between satellite spectral data and land cover data from ground data and photo interpretation to predict a cover or a tree-size value for image pixels where there are no ground data.

The Vegetation Strike Team Standards define the total tree crown closure as the percent of ground covered by the vertical projection of the outermost perimeter of the natural spread of the tree foliage. In the IVMP, this includes trees, shrubs and herbs. This vegetation cover was predicted continuously in 1% increments with 25-m^2 spatial resolution.

Tree sizes were estimated in the IVMP project using the quadratic mean diameter (QMD) defined as the diameter at the breast height (DBH) of a tree of average basal area for the stand. Due to the nature of the land cover and the lack of the field data, supervised and unsupervised classifications were used for the tree size coverage. In an unsupervised classification, the pixels are sorted into clusters based on similar numbers in all spectral bands where the land cover type is represented by each spectral group. In a supervised technique, training samples are built for each cover type followed by an automatic classification procedure. The following QMD classes were mapped: 0-4.9", 5-9.9", 10-19.9" and 20"+.

The species likely to dominate the Wenatchee Forest area, which includes the Wenatchee River basin, following an extended disturbance-free period were identified in Lillybridge et al. (1995) and summarized in Whiley and Cleland (2003): ponderosa pine/shrub-steppe, Douglas-fir, Douglas-fir/grand fir, grand fir/western hemlock, western hemlock, Pacific silver fir/ mountain hemlock, and sub-alpine fir.

Potential near-stream vegetation cover characteristics (tree height and optimal canopy cover) were determined summarizing the IVMP GIS data in 100m (each side or 200 m total) buffers created along the stream polylines. Tree height was estimated using the power function developed by Whiley and Cleland (2003) in the Wenatchee Forest temperature TMDL study for all the above vegetation species:

$$\text{height}_{\textit{in feet}} = 17.65 * \text{DBH}_{\textit{in inch}}^{0.59}$$

The DBH in this equation is estimated as a weighted average. The proportions of each of the QMD classes were estimated individually for each of the investigated stream buffers. For example, the representation of QMD classes in the 100-m riparian buffer along Icicle Creek is illustrated in Table 9.

Table 9. QMD classes in the Icicle Creek riparian buffer.

QMD class	% of riparian area corresponding to each QMD class
0 – 4.9"	0.14
5 – 9.9"	0.18
10 – 19.9"	0.58
20" +	0.10

To estimate an average tree size at mature stages for the whole corridor, a weighted average for the DBH value was calculated as following:

$$\text{DBH}_{\text{Icicle Creek}} = 0.14*4.9 + 0.18*9.9 + 0.58*19.9 + 25*25 = 16.51"$$

The maximum value of each class (e.g., for the 0-4.9" class, 4.9" was chosen) was used to estimate mature vegetation. The same method was used to estimate the optimal canopy density using four density classes: 0-10%, 10-40%, 40-70%, and 70-100%.

The estimated near-stream potential vegetation height and density in the Wenatchee River basin are presented in Table 10.

Table 10. Near-stream potential vegetation heights and densities in the Wenatchee River basin.

Waterbody	River mile	Vegetation height (m)	Vegetation density (%)
Mainstem	0 to 27.1	26	37
Wenatchee River	27.1 to headwaters	27	75
Icicle Creek		28	85
Nason Creek		25	85
Peshastin Creek		27	66
Mission Creek		28	69
Average for the whole basin		28	77

To estimate the potential shade levels in the Wenatchee River basin, potential vegetation characteristics determined using the IVMP data were used. These estimates were the most comprehensive as they offer information on the near-stream potential tree heights and densities for each of the analyzed streams. These estimates are greater than the estimates provided by Terry Lillybridge. However, they are assumed to approximate both the natural growth and expansion of the riparian vegetation, as well as the riparian restoration efforts.

Effective shade calculations

Vegetation data were input into a shade model (Ecology, 2003a). The vegetation codes required for input in this model were sampled with Ttools 3.3 ArcView extension developed by the Oregon Department of Environmental Quality (ODEQ, 2001) at 100-meter intervals. The shade calculation method chosen was the method developed by Chen (1996). Other data required by the shade model include stream aspect and topographic shade angles to the west, south, and east. The shade levels are determined mostly by the time of year, solar position, geographic position, stream geomorphology, and riparian vegetation.

Effective shade levels provided by vegetation and topography (Figure 26) were estimated for the Wenatchee River, Icicle Creek, Nason Creek, Peshastin Creek, and Mission Creek for three scenarios:

- topography only
- current vegetation and topography
- mature riparian vegetation with characteristics presented in Table 10, and topography

Figure 27 presents the effective shade deficit and the percent improvement in effective shade levels in the Wenatchee River basin.

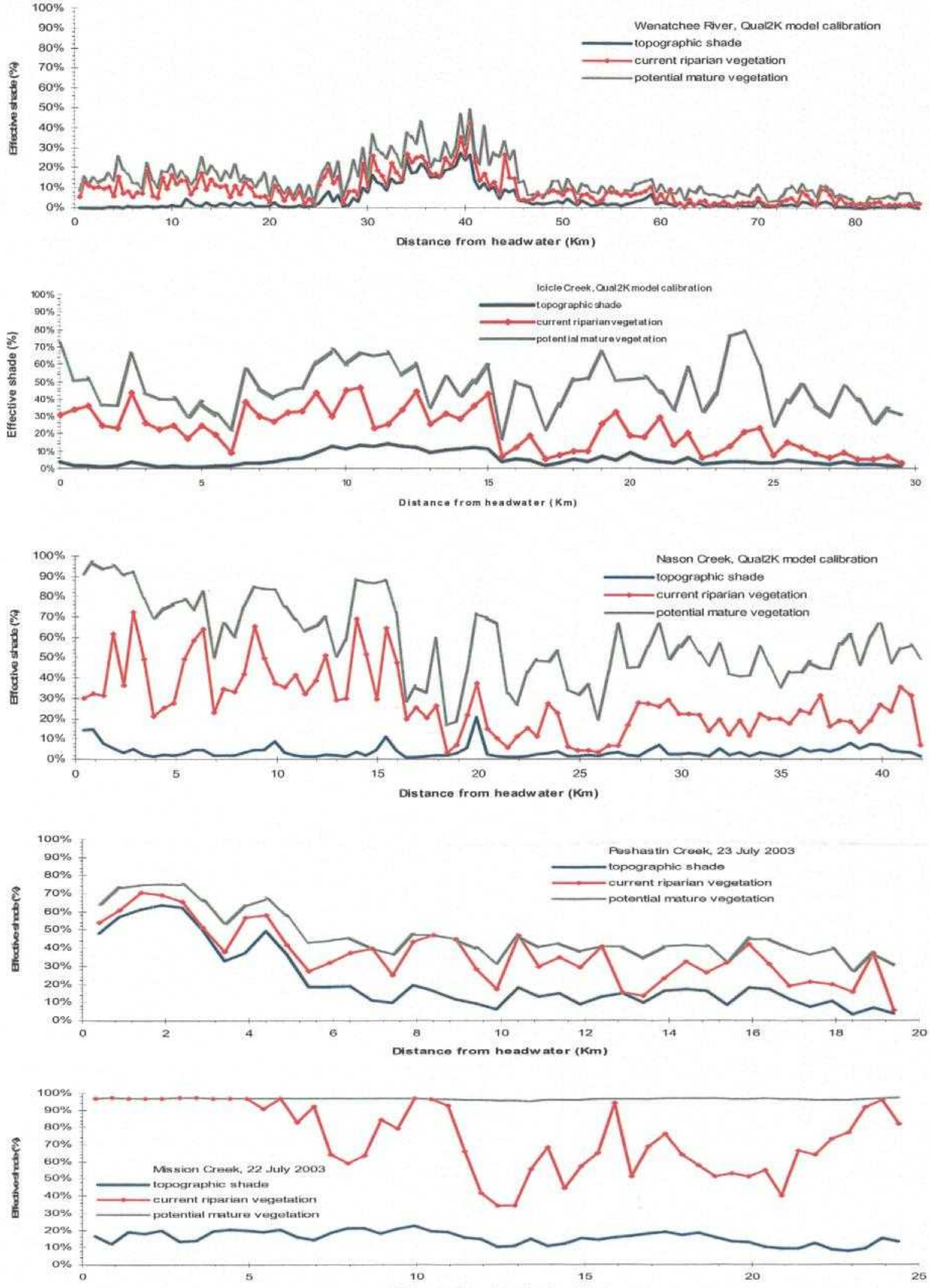
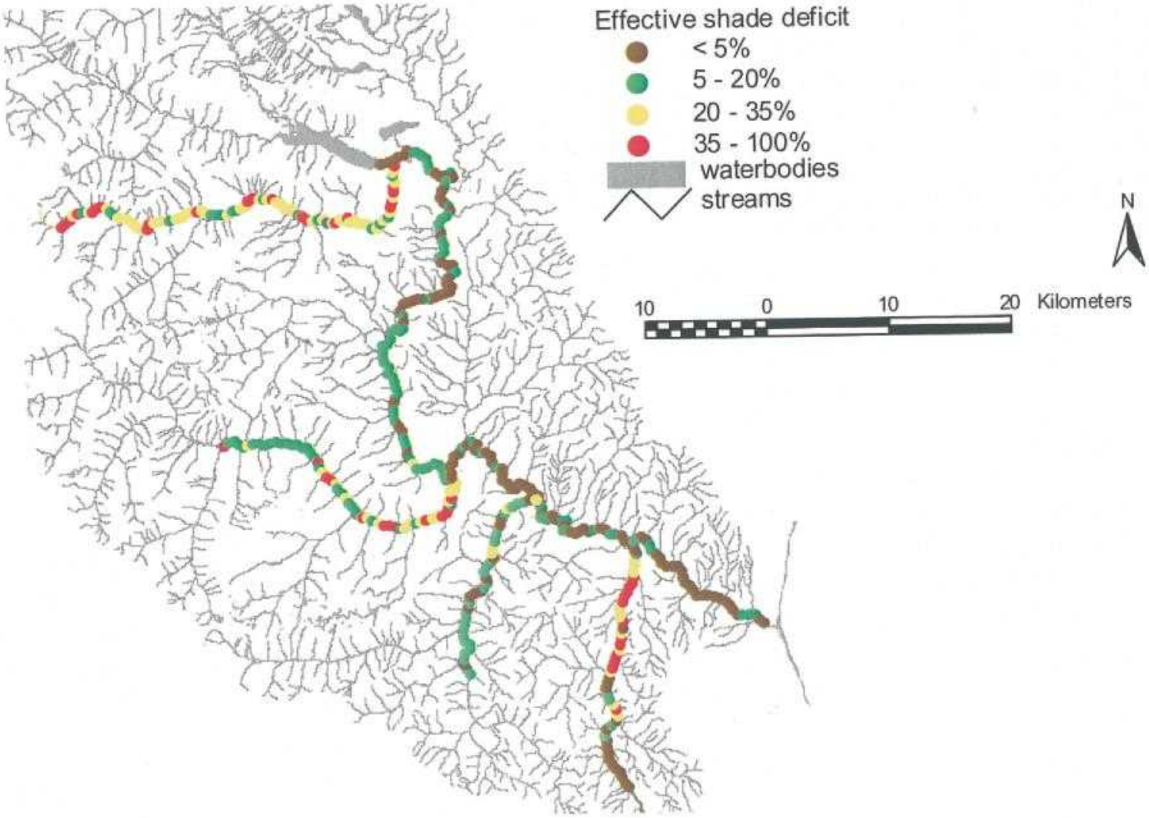


Figure 26. Effective shade from topography, current riparian vegetation, and potential mature vegetation in the Wenatchee River basin.



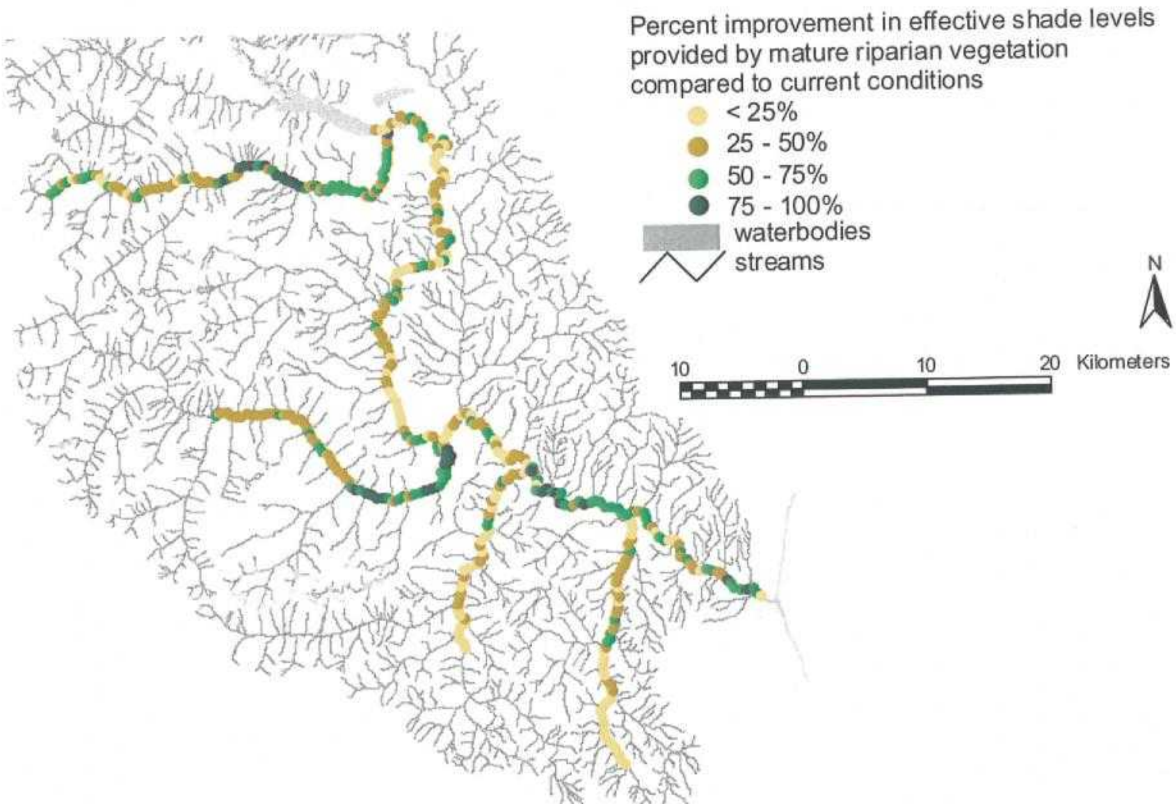


Figure 27. Effective shade deficit and percent improvement in effective shade levels in the Wenatchee River basin.

Analytical framework

Data collected during this TMDL study allow the development of a temperature simulation model that is both spatially continuous and which spans full-day lengths (steady flow, dynamic heat budget, and water temperature). The GIS and modeling analyses use three specialized software tools:

1. ODEQ's Ttools extension for ArcView (ODEQ, 2001) was used to sample and process GIS data for input to the Shade and QUAL2Kw models.

2. Ecology's Shade model (Ecology, 2003a) was used to estimate effective shade along the mainstems of the major tributaries in the Wenatchee River basin. Effective shade was calculated at 100-meter intervals along the streams and then averaged over 500-meter intervals for input to the QUAL2Kw model.

3. The QUAL2Kw model (Pelletier and Chapra, 2003; Chapra and Pelletier, 2003) was used to calculate the components of the heat budget and to simulate water temperatures. QUAL2Kw simulates diurnal variations in stream temperature for a steady flow condition. QUAL2Kw was applied by assuming that flow remains constant for a given condition such as a 7-day or 1-day period, but key variables are allowed to vary with time over the course of a day. For temperature simulation, the solar radiation, air temperature, relative humidity, headwater temperature, and tributary water temperatures were specified or simulated as diurnally varying functions. QUAL2Kw uses the kinetic formulations for the components of the surface water heat budget that are shown in Figure 4 and described in Chapra (1997). Diurnally varying water temperatures at 500-meter intervals along the streams in the Wenatchee River basin were simulated using a finite difference numerical method.

All input data for the Shade and QUAL2Kw models are longitudinally referenced, allowing spatial and/or continuous inputs to apply to certain zones or specific river segments. Model input data were determined from available GIS coverages using the Ttools extension for ArcView, or from data collected by Ecology or other data sources. Detailed spatial data sets were developed for the following parameters for model calibration and verification:

- The Wenatchee River, Icicle Creek, Nason Creek, Peshastin Creek, and Mission Creek were mapped at 1:3,000 scale from 1-meter-resolution Digital Orthophoto Quads (DOQ).
- Near-stream disturbance zone (NSDZ) widths were digitized at 1:3000 scale.
- West, east, and south topographic shade angle calculations were made from the 10-meter DEM grid using ODEQ's Ttools extension for ArcView.
- Stream elevation and gradient were sampled from the 10-meter DEM grid with the ArcView Ttools extension. Gradient was calculated from the longitudinal profiles of elevation from the 10-meter DEM.
- Aspect (streamflow direction in decimal degrees from north) was calculated by the Ttools extension for ArcView.

- The daily minimum and maximum observed temperatures for the boundary conditions at the headwaters and tributaries were used as input to the QUAL2Kw model for the calibration and verification periods.
- Flow balances for the preliminary calibration and verification periods were estimated from field measurements and gage data of flows made by Ecology and the USGS. A flow balance spreadsheet of the stream networks for the Wenatchee River, Icicle Creek, and Nason Creek was constructed to estimate surface water and groundwater inflows by interpolating between the gaging stations.
- Hydraulic geometry (wetted width, depth, and velocity as a function of flow) was estimated using wetted widths that were digitized from DOQs and scaled to different river flows using the average power functions from the USGS gaging stations. Velocities were estimated from dye study data and scaled to different river flows using the average power functions from the USGS gaging stations.
- The temperature of groundwater is often assumed to be similar to the mean annual air temperature (Theurer et al, 1984). Calibration of the QUAL2Kw model involved selection of the temperature of diffuse inflows, ranging from the estimated temperature of groundwater temperature to observed temperatures of surface water tributaries.

Calibration and confirmation of the QUAL2Kw model

The August 10-16, 2002 period (the hottest 7-day period of 2002) was used to calibrate the QUAL2Kw water quality model for the Wenatchee River and Icicle Creek. The TIR survey for both streams took place on August 16, 2002; therefore, the TIR-derived temperature data could be compared to the model results. The calibration, however, was performed using the 7-day averages of the instream data logger values. A cool period of September 9-11, 2002 was used to confirm the stream temperature model.

Due to the construction of the Leavenworth National Fish Hatchery (LNFH) in 1939-1940, the flow of Icicle Creek was split into two distinctive channels: a man-made canal and the historic stream channel (Figure 28). Two temperature models were set up for Icicle Creek: a reach that stretches from the river mouth to RM 19.3, including the historic stream segment, and the canal itself.

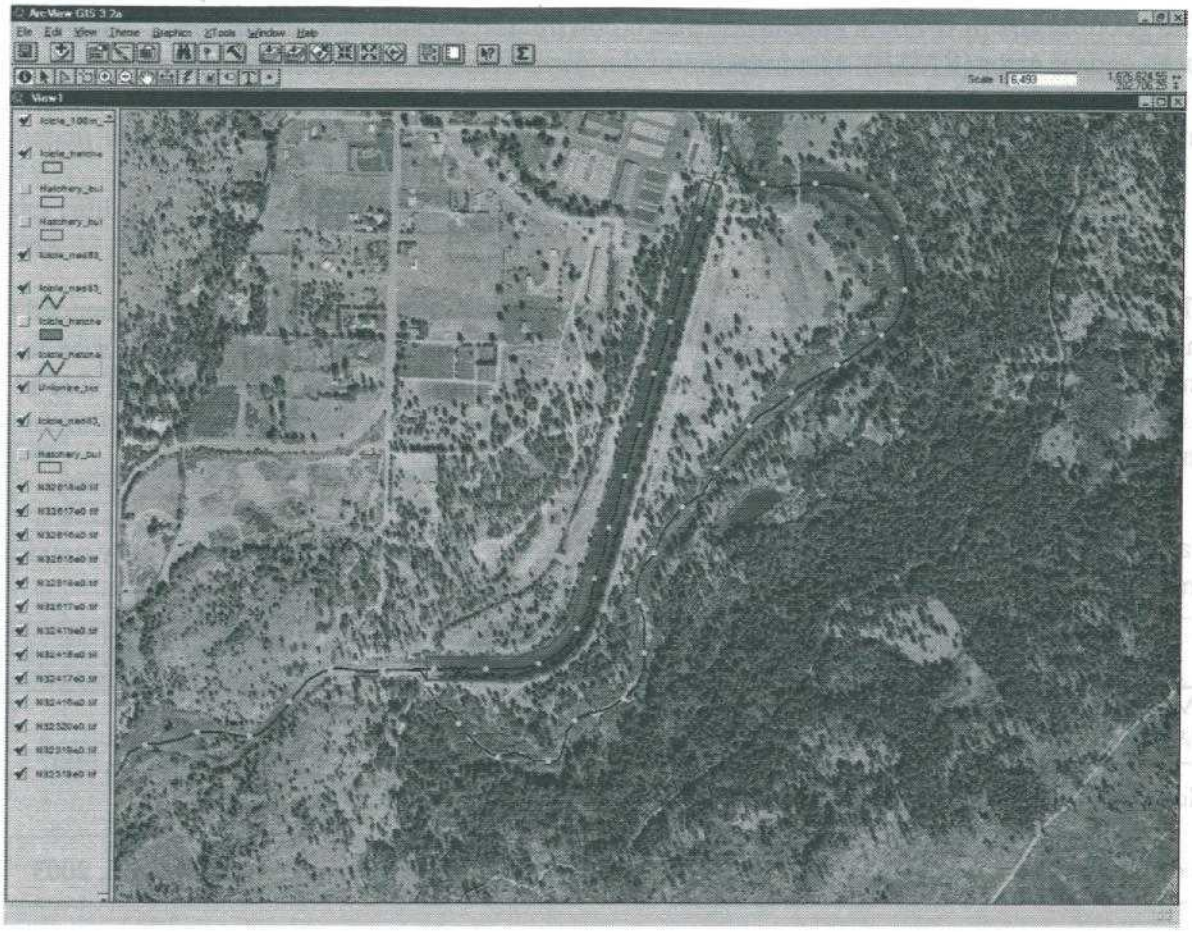


Figure 28. Icicle Creek historic channel and the Leavenworth National Fish Hatchery canal.

The model calibration and confirmation periods for Nason Creek are July 24-30, 2003 and August 11-13, 2003, respectively. A TIR survey of the creek was performed on August 12, 2003.

During the stream temperature monitoring period, data-loggers installed throughout the Wenatchee River watershed continuously recorded air temperature, and few data-loggers recorded relative humidity (Figure 23). Air temperatures were interpolated between reaches based on elevation using the air temperature data recorded at the tidbit data logger locations for model input. The dew point temperatures and wind were estimated as a function of elevation, using the weather data from the relevant meteorological stations located in the vicinity of the streams (e.g., Wenatchee TFREC, DOT Cashmere, DOT Dryden Road, and RAWS (Remote Automated Weather Stations) Dry Creek, or DOT Stevens Pass).

The goodness of fit for both calibration and confirmation periods was summarized using the root mean square error (RMSE), as a measure of the deviation of model-predicted stream temperature from the measured values. The RMSE represents an estimation of the overall model performance and was calculated as:

$$RMSE = \sqrt{\sum \frac{\left(T_{measured} - T_{calculated}\right)^2}{n}}$$

The headwater measurement location was not used in the computation because it influenced the model prediction as a headwater boundary condition. The RMSE were calculated for maximum and minimum predicted temperatures for both calibration and confirmation periods (Table 11). Additionally, for the Wenatchee River, RMSE were estimated for water temperature diurnal variation at the tidbit locations (Table 12).

Table 11. Summary of RMSE of differences between the predicted and observed daily maximum and minimum temperatures in the Wenatchee River basin.

Waterbody	Temperature	RMSE (deg C) Model *Calibration*		RMSE (deg C) Model *Confirmation*	
Mainstem Wenatchee River	Minimum	0.28	Aug 10-16, 2002	0.43	Sept 9-11, 2002
	Maximum	0.29		0.63	
Icicle Creek	Minimum	0.48		0.38	
	Maximum	0.27		0.49	
Nason Creek	Minimum	0.43	July 24-30, 2003	0.78	Aug 11-13, 2003
	Maximum	0.47		0.74	

Table 12. Summary of RMSE of differences between the predicted and observed maximum daily temperatures in the Wenatchee River basin – temporal variation.

Waterbody	Tidbit Location		RMSE (deg C) Model *Calibration* (Aug 10-16, 2002)	RMSE (deg C) Model *Confirmation* (Sept 9-11, 2002)
	River Mile	River Km		
Mainstem Wenatchee River	0.5	0.8	0.26	0.70
	5.3	8.5	0.46	0.63
	10.2	16.4	0.39	0.49
	14.1	22.7	0.40	0.67
	18.1	29.1	0.37	0.80
	18.7	30.1	0.57	1.07
	20.9	33.6	0.71	0.78
	23.6	38.0	0.58	-
	28.1	45.2	0.65	0.81
	30.3	48.8	0.92	1.16
	33.0	53.1	0.60	0.45
	46.4	74.7	0.45	0.38
	53.9	86.7	0.09	0.16

Km = kilometers

The predicted and measured maximum, mean, and minimum stream water temperature longitudinal profiles for the calibration and confirmation periods for the Wenatchee River are presented in Figure 29. Stream temperature temporal variations at several locations along the mainstem Wenatchee River are shown in Figure 30 and Figure 31.

Model calibration and confirmation results for Icicle Creek and Nason Creek are shown in Figures 32 and 33, respectively.

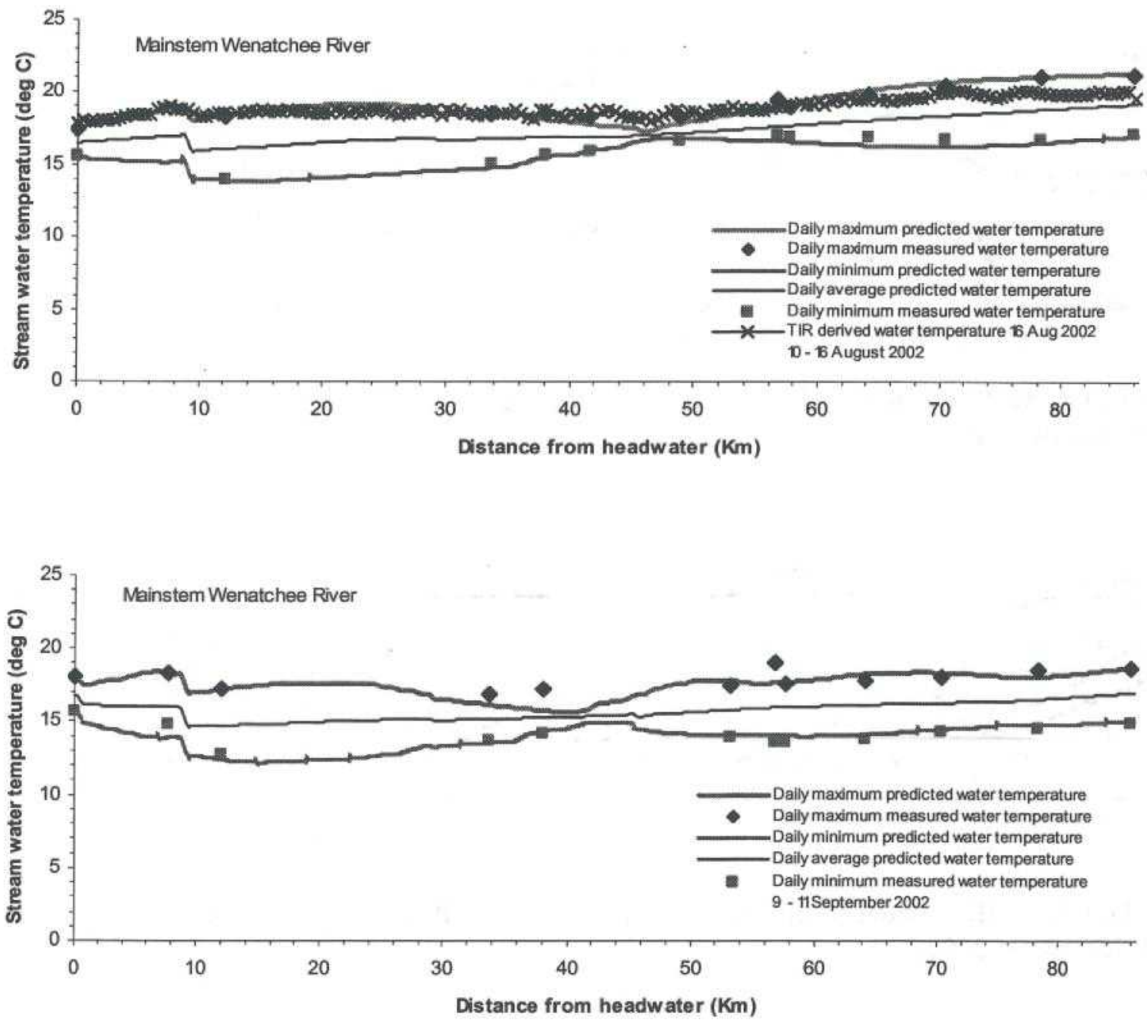


Figure 29. Predicted and observed water temperatures in the Wenatchee River at model calibration (10-16 August 2002) and model confirmation (9-11 September 2002).

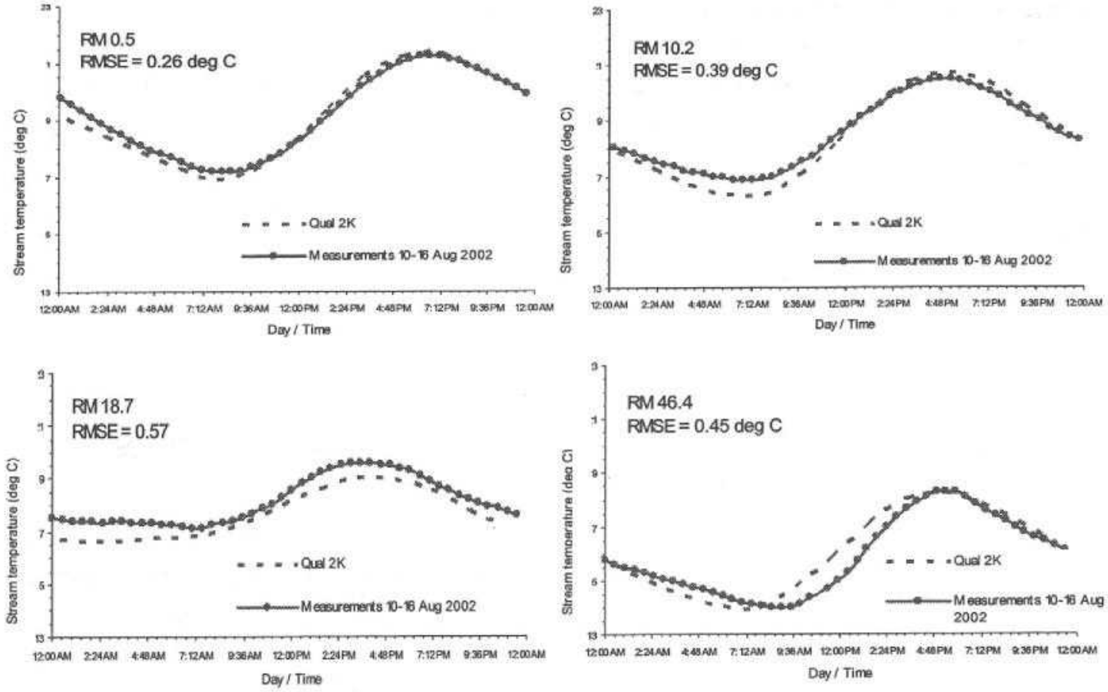


Figure 30. QUAL2Kw model calibration for the Wenatchee River temperature temporal variations (10 – 16 August 2002).

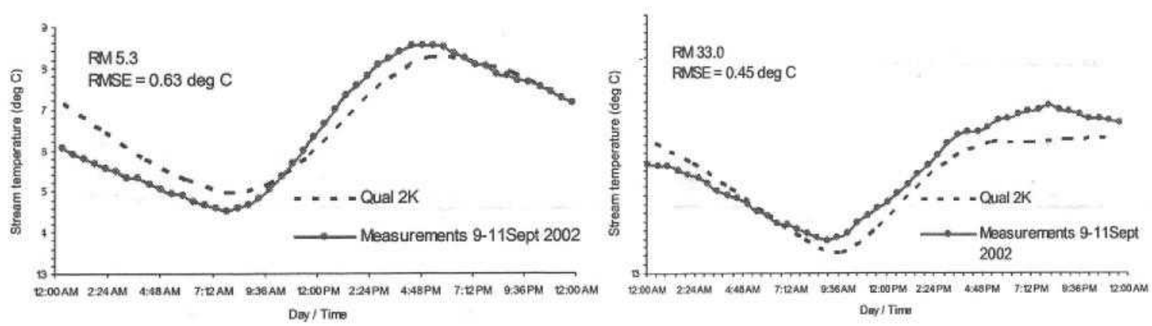


Figure 31. QUAL2Kw model confirmation for the Wenatchee River temperature temporal variations (9 – 11 September 2002).

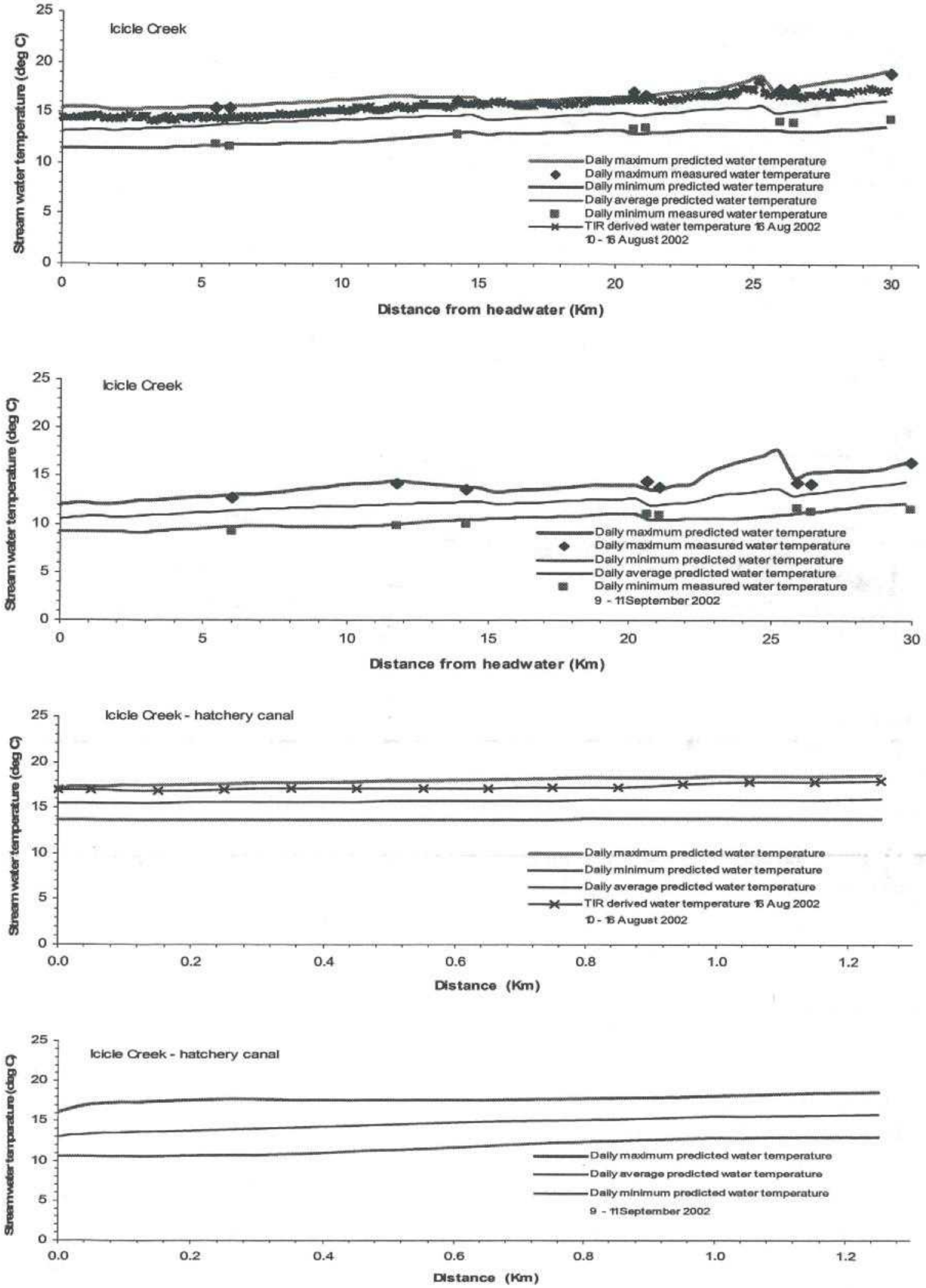
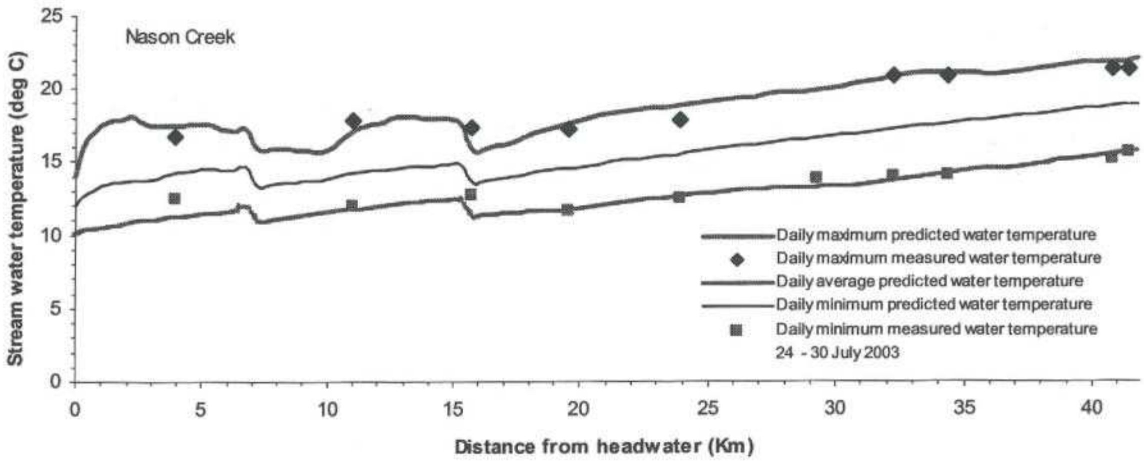


Figure 32. Predicted and observed water temperatures for Icicle Creek and LNFH canal at model calibration (10-16 August 2002) and model confirmation (9-11 September 2002).



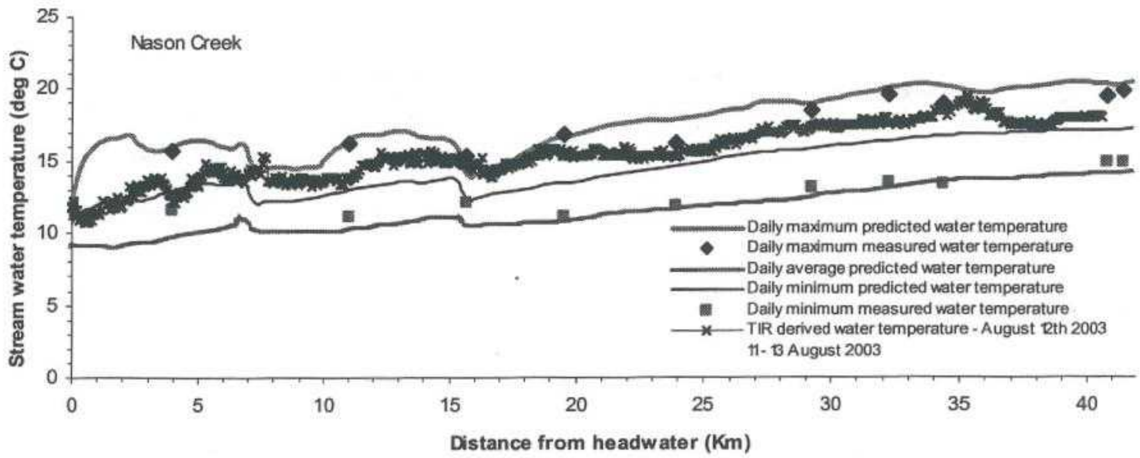


Figure 33. Predicted and observed water temperatures for Nason Creek at model calibration (24-30 July 2003) and model confirmation (11-13 August 2003).

Loading capacity

The loading capacity provides a reference for calculating the amount of pollutant reduction needed to bring water into compliance with standards. EPA's current regulation defines loading capacity as "the greatest amount of loading that a waterbody can receive without violating water quality standards" (40 CFR § 130.2(f)).

The system potential temperature is considered to be an approximation of the temperatures that would occur under natural conditions. In areas where the system potential temperature is greater than the numeric criterion of 18°C in Class A or 16°C in Class AA waters, then the natural conditions provision of the water quality standard is the basis of the loading capacity, load allocations, and wasteload allocations in this TMDL.

The calibrated QUAL2Kw model was used to determine the loading capacity for the studied streams in the Wenatchee River basin. Loading capacity was determined based on prediction of water temperatures under typical and extreme flow and climate conditions combined with a range of effective shade conditions.

The lowest 7-day average flow with a 2-year recurrence interval (7Q2) was selected to represent a typical climatic year, and the lowest 7-day average flow with a 10-year recurrence interval (7Q10) was selected to represent a worst-case condition for the July-August period. The recommended load allocations and wasteload allocations in later sections of this report are based on the 7Q10 condition.

Air temperatures for the 7Q2 flow conditions were assumed to be represented by the August 8-14, 2001 week corresponding to the median condition at the NOAA-COOP Leavenworth meteorological station. Air temperatures for the 7Q10 flow conditions were represented by the August 11-17, 2001 week corresponding to the 90th percentile condition at the same station.

The current thermal behavior of the river was estimated for the 7Q2 and 7Q10 flows associated with the historic median air temperature and historic 90th percentile air temperature, respectively. A series of scenarios that would help reduce the Wenatchee River water temperature were evaluated as follows:

- **Maximum potential shade.** This would be provided by mature riparian vegetation with tree heights and densities evaluated for each stream (Table 10).
- **Microclimate improvements.** The presence of mature riparian vegetation would induce changes in microclimate conditions along the river. The air temperature and the wind speed would decrease, and the relative humidity would increase. Bartholow (2000) indicated that mature riparian vegetation would reduce the air temperature by 2°C and would increase the relative humidity by 10%. The wind speed was decreased to 0.2 m/s.
- **Reduced channel widths.** A 10% reduction in channel widths was assumed for this simulation.
- **Conversion of consumptive withdrawals to instream flow.** The surface withdrawals were converted to increased streamflow.

For the Wenatchee River, an additional scenario that assumes tributary inputs at water quality standards (WQS) was also considered.

The results of the model runs for the critical 7Q2 and 7Q10 conditions are presented in Table 13 and Figures 34 through 36. The current condition in the Wenatchee watershed is expected to result in daily maximum temperatures that are greater than 18°C in most of the evaluated reaches. Portions of the studied streams are greater than the approximate threshold for lethality of 23°C under current conditions.

A climate change scenario was also investigated to evaluate the stream temperatures in the Wenatchee River basin for the July – August period.

Climate change research (Jones and Mann, 2004) reveals that the late unprecedented 20th Century anomalous warming may be due to the anthropogenic impact on the environment. Climate change could affect the availability and the dynamics of water resources in the Pacific Northwest. The instream flows in the dry season depend on the snowpack stored in the wet season. Increases in air temperature will affect the amount of water stored in the snowpack, as more precipitation will fall as rain rather than snow during the wet season.

Climate simulation models predict increases in air temperatures in the Pacific Northwest by 1.7 – 3.5°C, with an average of 2.8°C from 2000 to 2050. Under such scenarios, precipitation is anticipated to increase by about 10% on average in the wet season, but the average change in precipitation in the dry season is close to zero (Mote et al., 2001).

Hamlet (2004) showed that water availability in the Columbia River basin (which includes the Wenatchee River basin) is affected by climate change especially during the summer months. The reduced area and depth of the snowpack and elevated spring and summer air temperatures melt the snow sooner, increasing the summer evapotranspiration and decreasing the summer and fall streamflow by an average of 25% by 2050.

The stream temperature models were run considering a climate change scenario: an increase in air temperatures by 2.8°C and a decrease in 7Q10 by 25%. The other scenarios discussed previously were tested sequentially on the climate change setting of the model. The results of these model runs are presented in Table 13 and Figures 34 through 36.

The "lethality" limit in Figures 33 through 35 is referring to the following excerpt from an Ecology study (Hicks, 2002) that evaluates lethal temperatures for coldwater fish:

"For evaluating the effects of discrete human actions, a 7-day average of the daily maximum temperatures greater than 22°C or a 1-day maximum greater than 23°C should be considered lethal to cold water fish species such as salmonids. Discharge plume temperatures should be maintained such that fish could not be entrained (based on plume time of travel) for more than 2 seconds at temperatures above 33°C to avoid creating areas that will cause near instantaneous lethality. Barriers to migration should be assumed to exist anytime daily maximum water temperatures are greater than 22°C and the adjacent down-stream water temperatures are 3°C or more cooler."

Table 13. Summary of average predicted daily mean/maximum water temperatures (deg C) at critical conditions in the Wenatchee River basin.

	Wenatchee River			Icicle Creek			Nason Creek		
Scenario									
7Q2	Tmean	Tmax	Tmax of all reaches	Tmean	Tmax	Tmax of all reaches	Tmean	Tmax	Tmax of all reaches
current condition	19.1	21.4	25.0	15.8	18.3	21.8	16.5	19.9	22.7
mature riparian vegetation	18.9	21.1	24.5	15.1	17.1	19.7	14.6	17.0	19.1
plus microclimate improvement	18.6	20.8	24.0	14.9	16.8	19.0	14.1	16.3	18.8
plus reduced channel widths	18.3	20.4	23.3	14.7	16.5	18.8	14.1	16.0	18.4
plus convert surface withdrawals to instream flow	18.3	20.3	22.7	14.9	16.4	18.3	14.1	16.0	18.3
plus tributary inputs at WQS	18.2	20.2	22.7						
7Q10	Tmean	Tmax	Tmax of all reaches	Tmean	Tmax	Tmax of all reaches	Tmean	Tmax	Tmax of all reaches
current condition	21.8	24.4	29.0	16.1	19.0	22.3	17.6	22.1	25.5
mature riparian vegetation	21.5	24.1	28.6	15.3	17.6	20.1	15.2	18.3	21.1
plus microclimate improvement	21.0	23.5	27.1	15.2	17.4	19.6	14.6	17.4	21.1
plus reduced channel widths	20.8	23.1	26.4	15.0	17.0	19.6	14.6	17.1	20.4
plus convert surface withdrawals to instream flow	20.7	23.0	25.6	15.0	17.2	19.0	14.6	17.1	20.4
plus tributary inputs at WQS	20.5	22.7	25.3						
Climate Change Scenario									
7Q2	Tmean	Tmax	Tmax of all reaches	Tmean	Tmax	Tmax of all reaches	Tmean	Tmax	Tmax of all reaches
current condition	19.1	21.4	25.0	15.8	18.3	21.8	16.5	19.9	22.7
climate change	20.8	23.2	28.5	16.6	19.4	23.3	17.9	21.8	25.1
mature riparian vegetation	20.5	22.8	28.1	15.8	18.1	21.1	15.8	18.5	21.3
plus microclimate improvement	20.0	22.4	26.9	15.5	17.6	20.1	14.8	17.1	20.5
plus reduced channel widths	19.7	21.8	26.1	15.3	17.3	20.1	14.8	17.0	20.4
plus convert surface withdrawals to instream flow	19.6	21.7	25.4	15.8	17.5	19..8	14.8	16.9	20.3
plus tributary inputs at WQS	19.6	21.7	25.3						
7Q10	Tmean	Tmax	Tmax of all reaches	Tmean	Tmax	Tmax of all reaches	Tmean	Tmax	Tmax of all reaches
current condition	21.8	24.4	29.0	16.1	19.0	22.3	17.6	22.1	25.5
climate change	23.4	26.3	32.0	17.5	20.7	28.3	19.3	24.2	28.5
mature riparian vegetation	23.1	26.0	31.5	16.4	19.1	25.0	16.8	20.2	23.7
plus microclimate improvement	22.4	25.3	29.7	16.1	18.6	24.0	15.5	18.6	23.3
plus reduced channel widths	22.1	24.7	28.9	16.0	18.4	24.0	15.4	18.2	22.1
plus convert surface withdrawals to instream flow	22.0	24.5	27.8	16.7	18.6	20.8	15.4	18.2	22.0
plus tributary inputs at WQS	21.9	22.4	27.7						

Note: The maximum temperatures of all reaches usually occur in the lower reaches (close to the mouth) for the Wenatchee River and Nason Creek. For Icicle Creek, the maximum simulated temperatures occur in the old channel.

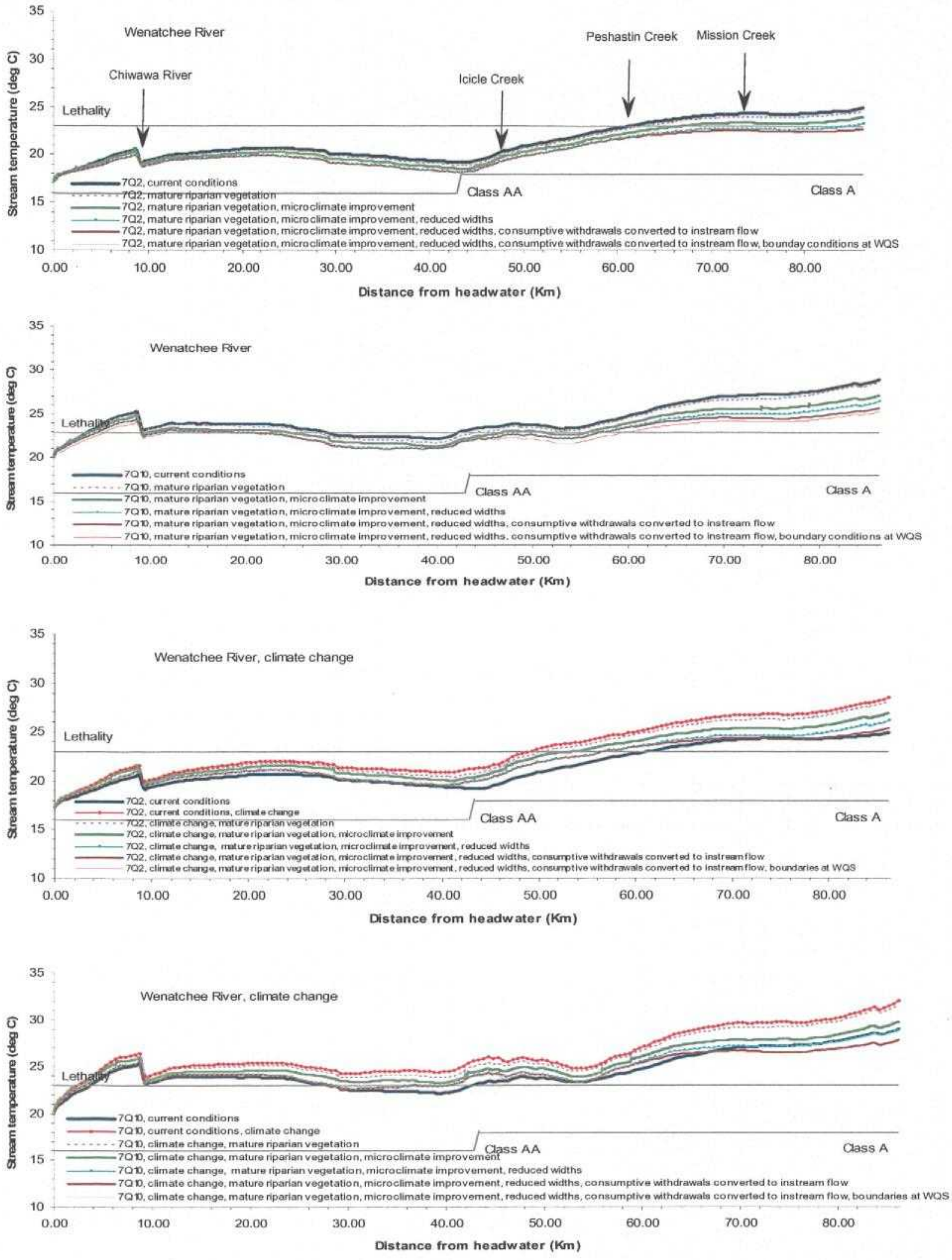


Figure 34. Predicted daily maximum water temperatures in the Wenatchee River for critical conditions during July-August 7Q2 and 7Q10.

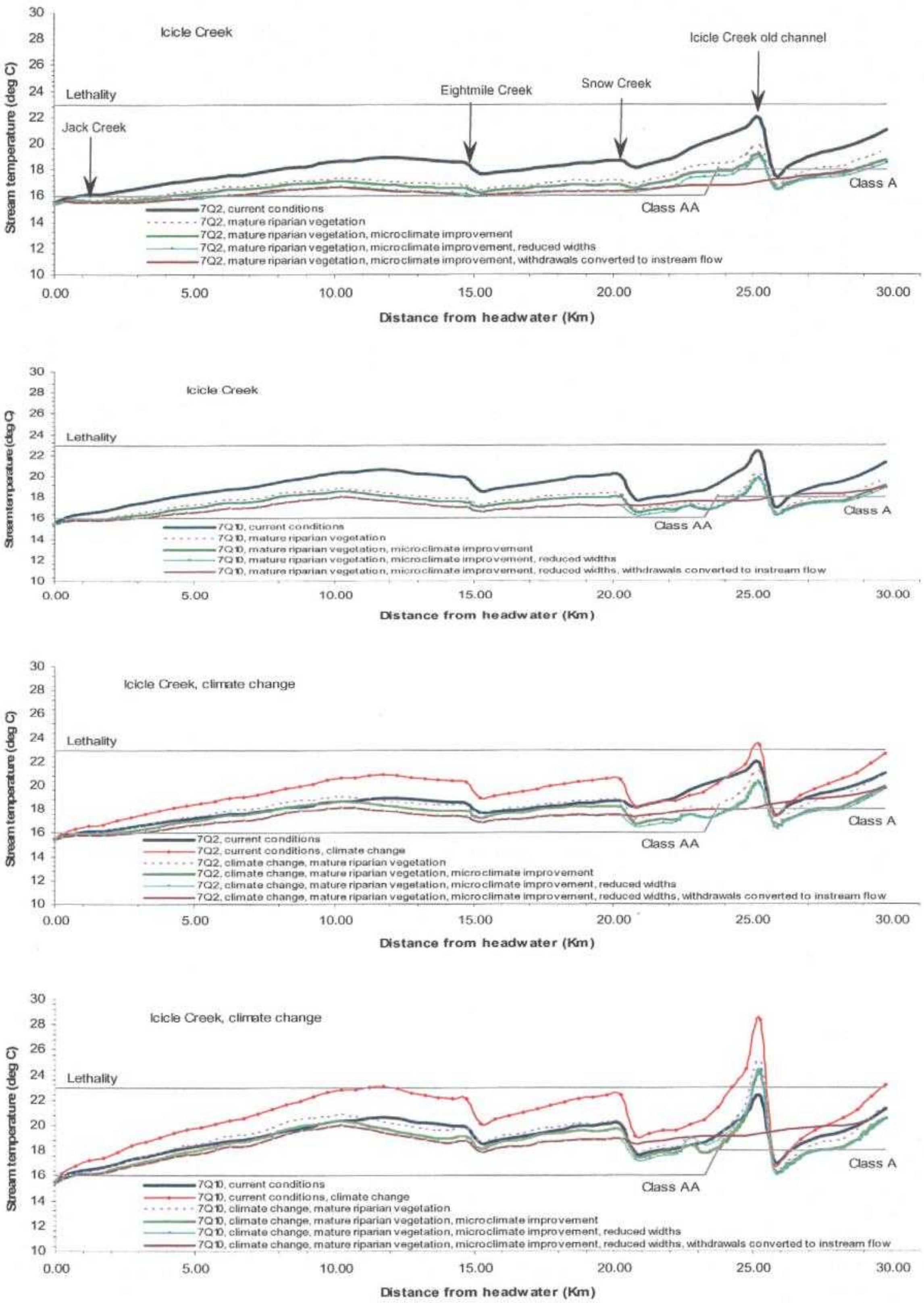


Figure 35. Predicted daily maximum water temperatures for Icicle Creek for critical conditions during July-August 7Q2 and 7Q10.

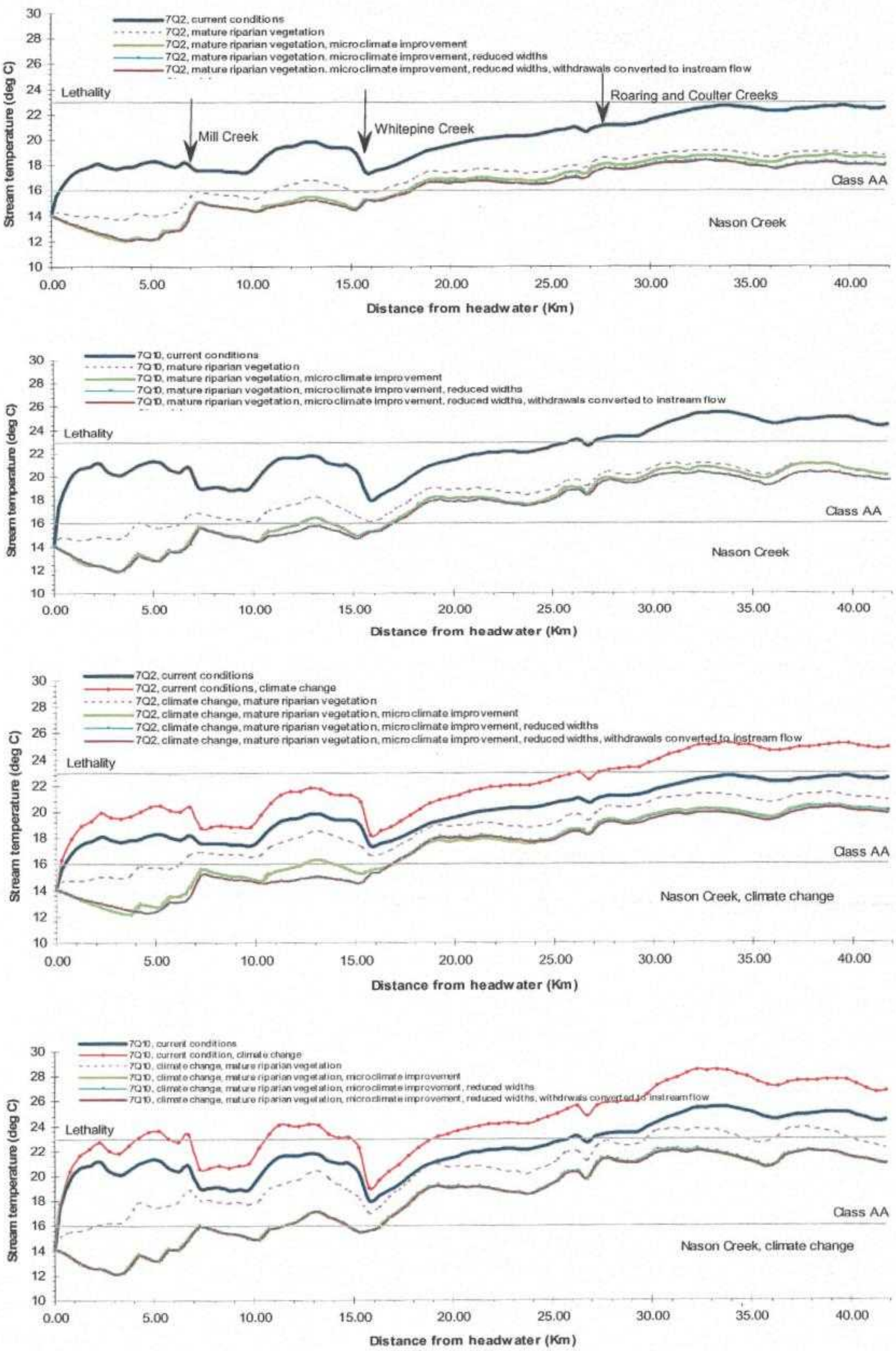


Figure 36. Predicted daily maximum water temperatures for Nason Creek for critical conditions during July-August 7Q2 and 7Q10.

Figure 37 illustrates the influence of Lake Wenatchee on the temperature of the Wenatchee River. The two longitudinal profiles represent the improved 7Q10 condition of the Wenatchee River with different headwater conditions. The first assumption for the headwater conditions was derived from the 2001 TIR survey that took place on a very hot day and close to 7Q10 flows. The second assumption assumes lake water temperature at water quality standards for Class AA waters (16°C).

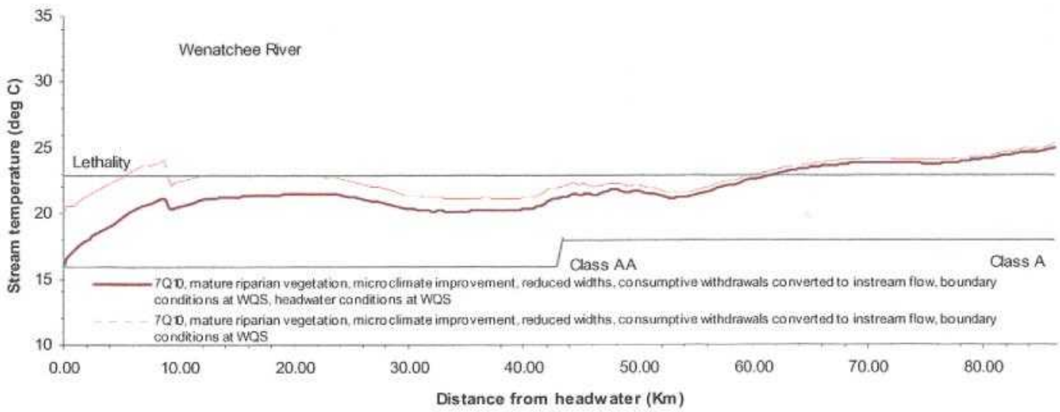


Figure 37. Predicted daily maximum water temperatures in the Wenatchee River for critical conditions during July-August and 7Q10 flow assuming two different headwater conditions.

The QUAL2Kw model simulations indicated that:

1. A buffer of mature riparian vegetation along the banks of the rivers is expected to decrease the average daily maximum temperatures. At 7Q10 flow conditions, the lowest reduction of only 0.3°C is expected for the Wenatchee River. Significant reductions of 3.8°C and 1.4°C are expected for Nason Creek and Icicle Creek, respectively. On average, a 1.8°C reduction in the average daily maximum temperatures is expected for the studied streams.

2. The changes in microclimate conditions associated with mature riparian vegetation could further lower the daily average maximum water temperature by about 0.6°C.

3. Lake Wenatchee is the source of the Wenatchee River; therefore, the headwater boundary conditions were imposed by the thermal behavior of Lake Wenatchee, which is currently classified as oligotrophic with no major water quality problems.

4. A 10% reduction in channel width could decrease the daily average maximum water temperature by about 0.4°C.

5. The conversion of withdrawals into instream flow had little effect on the reach-average stream maximum temperature of the Wenatchee River, diminishing it by 0.1°C. The withdrawal locations are in the lower half of the river; therefore, the influence of increased streamflows only had a noticeable effect on the stream water temperature in the lower reaches. The increased streamflows led to a decrease in the maximum (across all reaches) simulated water temperature by 0.8°C. The scenario assuming the boundary conditions at water quality standards shows an average reduction of about 0.3°C at 7Q10 flow conditions.

6. For Icicle Creek, the conversion of withdrawals into instream flow scenarios indicates an increase in the average daily maximum temperatures by about 0.2°C at 7Q10 flow conditions. The lower Icicle Creek flow regimes are impacted mostly by the water withdrawals necessary for irrigation and the fish hatchery. Currently, water returns from these water uses usually have a lower temperature than the mainstem and can slightly cool down the lower reaches of Icicle Creek.

7. Water withdrawals for Nason Creek are not significant, and their conversion to instream flow did not impact the reach-average stream temperature.

8. The overall decrease in the average maximum simulated temperature from the current conditions at 7Q10 was 2.7°C. The improvements considered in the simulation scenarios can lower the maximum simulated water temperature by as much as 3.4 to 5.1°C, with major changes in stream water temperature occurring mostly in the lower reaches of the rivers.

9. Model simulations performed under the 7-day average with 10-year return period flow conditions and climate change influences show that the average maximum temperature across all reaches can increase by as much as 2.0°C compared to the current conditions.

Load allocations

The natural conditions provision of the water quality standard is the basis of the load allocations in this TMDL (WAC 173-201A-070(2)):

"Whenever the natural conditions of said waters are of a lower quality than the criteria assigned, the natural conditions shall constitute the water quality criteria."

The natural condition of temperature was approximated by the system potential temperature, which was an evaluation of the combined effect of hypothetical conditions with mature riparian vegetation, microclimate improvements.

The load allocations are expected to result in water temperatures that are equivalent to the temperatures that would occur under natural conditions. Therefore, the load allocations are expected to result in water temperatures that meet the water quality standard.

The load allocation for effective shade for all perennial streams in the Wenatchee River watershed is the maximum potential shade that would occur from mature riparian vegetation.

Establishment of mature riparian vegetation is expected to also have a secondary benefit of reducing channel widths and improving microclimate conditions to address those influences on the loading capacity. An adaptive management strategy is recommended to address other influences on stream temperature such as sediment loading, groundwater inflows, and hyporheic exchange.

Load allocations for effective shade are quantified in Appendix B for the Wenatchee River, Icicle Creek, and Nason Creek.

For other perennial streams in the watershed, the load allocations for effective shade are represented in Figure 38 and Appendix C, based on the estimated relationship between shade, channel width, and stream aspect at the assumed maximum riparian vegetation condition: 77% density and 28 m tree height. Figure 38 shows that the importance of shade decreases as the width of the channel increases.

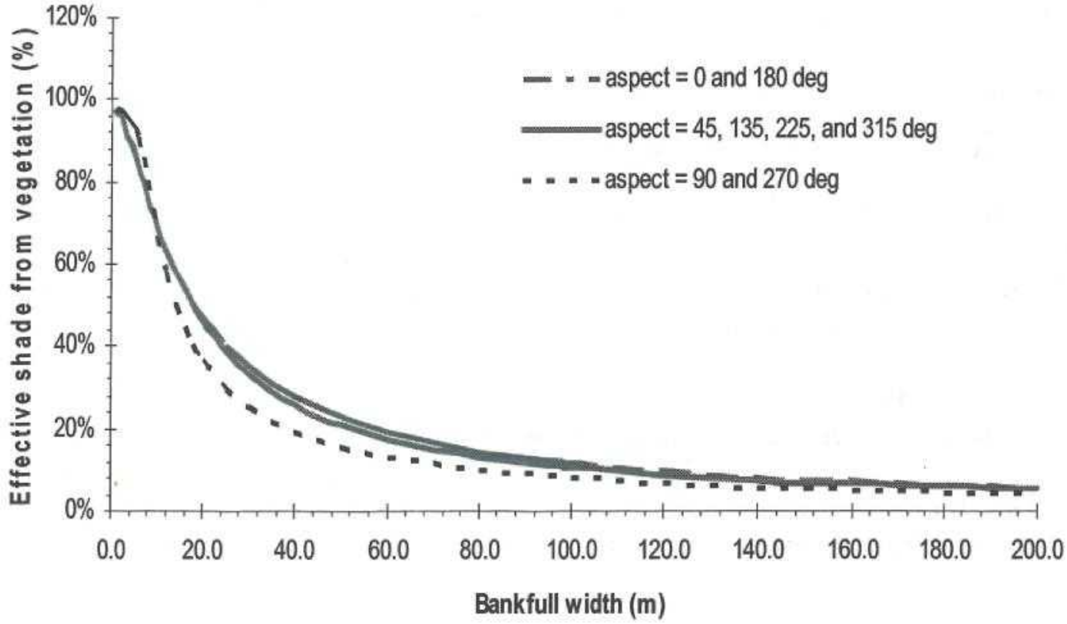


Figure 38. Load allocations for effective shade for various bankfull width and aspect of streams in the Wenatchee River basin assuming a riparian vegetation height of 28 m and a canopy density of 77%.

Wasteload allocations

The provisions in the water quality standard for natural conditions (WAC 173-201A-070(2)) and the allowable increase in temperature over natural conditions (WAC 173-201A-030(1)(c)(iv) for Class AA and WAC 173-201A-030(2)(c)(iv) for Class A) are the basis of the wasteload allocations in this TMDL:

"Whenever the natural conditions of said waters are of a lower quality than the criteria assigned, the natural conditions shall constitute the water quality criteria."

"...When natural conditions exceed 16°C (in Class AA waters)..., no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3°C."

"...When natural conditions exceed 18°C (in Class A waters)..., no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3°C."

The load allocations for the nonpoint sources are considered to be sufficient to attain the water quality standards by resulting in water temperatures that are equivalent to natural conditions. Therefore, the water quality standards allow an increase over natural conditions for the point sources for establishment of the wasteload allocations.

Wasteload allocations for the National Pollution Discharge Elimination System (NPDES) discharges were evaluated for the Wenatchee River basin. Maximum temperatures for NPDES effluent discharges (T_{NPDES}) were calculated from the following mass balance equation for system potential upstream temperatures greater than or equal to 16°C (all point sources in this TMDL study discharge to waters that are designated as Class AA) or 18°C (all point sources discharge to waters that are designated as Class A).

Class AA: T_{NPDES} = [16°C] + [chronic dilution factor] * 0.3°C

Class A: T_{NPDES} = [18°C] + [chronic dilution factor] * 0.3°C

Maximum effluent temperatures should also be no greater than 33°C to avoid creating areas in the mixing zone that would cause instantaneous lethality.

Table 14 presents the maximum effluent temperatures that would cause an increase of 0.3°C for various upstream receiving water temperatures for the reported dilution factors. The system potential temperatures upstream from the NPDES dischargers may be greater than 16°C for Class AA waters or 18°C for Class A waters and vary depending on the river flow and weather conditions. In Table 15 the maximum effluent temperatures were re-evaluated using the revised standard.

Table 14. Wasteload allocation (WLA) for effluent temperatures for selected NPDES dischargers in the Wenatchee River basin for the current standard.

NPDES Facility	Chronic dilution factor	Water quality standard for temperature (deg C)	Allowable increase in temperature at the mixing zone boundary (deg C)	T_{NPDES} = Maximum allowable effluent temperature WLA (deg C)
Lake Wenatchee	214	16	0.3	33.0
Stevens Pass	1	16	0.3	16.3
Cashmere	100	18	0.3	33.0
Leavenworth	37.1	18	0.3	29.1
Peshastin	331.7	18	0.3	33.0
National Fish Hatchery	1	18	0.3	18.3

Table 15. Wasteload allocation (WLA) for effluent temperatures for selected NPDES dischargers in the Wenatchee River basin for the revised standard.

NPDES Facility	Chronic dilution factor	Water quality standard for temperature (deg C)	Allowable increase in temperature at the mixing zone boundary (deg C)	T_{NPDES} = Maximum allowable effluent temperature WLA (deg C)
Lake Wenatchee	214	16	0.3	33.0
Stevens Pass	1	16	0.3	16.3
Cashmere	100	17.5	0.3	33.0
Leavenworth	37.1	17.5	0.3	28.6
Peshastin	331.7	17.5	0.3	33.0
National Fish Hatchery	1	17.5	0.3	17.8

Margin of safety

The margin of safety accounts for uncertainty about pollutant loading and waterbody response. In this TMDL, the margin of safety is addressed by using critical conditions in the modeling analysis. The margin of safety in this TMDL is implicit because of the following:

- The 90th percentile of the highest 7-day averages of daily mean air temperatures for the NOAA-COOP Leavenworth meteorological station was used as a worst-case condition for model simulations. Typical meteorological conditions were represented by the median condition at the same station.
- The lowest 7-day average flows during July-August with 10-year recurrence intervals (7Q10) were used for the worst-case scenario. Typical flow conditions were represented by the lowest 7-day average flows during July-August with recurrence intervals of 2 years (7Q2).
- Model uncertainty for prediction of water temperature was assessed by estimating the root mean square error (RMSE) of model predictions compared with observed temperatures. The average RMSE for model calibration and confirmation of maximum was 0.47°C.
- The load allocations are set to the effective shade provided by full mature riparian shade which are the maximum values achievable in the Wenatchee River basin.

Conclusions and Recommendations

1. The observed stream temperatures in the Wenatchee River watershed during 2002 and 2003 showed that current conditions at many locations are warmer than the current and proposed revised water quality criteria. In addition, many sites were found to be cooler than the temperature criteria. In general, warmer temperatures were found at downstream locations in the Wenatchee River, Icicle Creek, and Nason Creek, and cooler temperatures were found in headwater locations or relatively small tributaries. Stream temperature is increased in the historic channel of Icicle Creek due to the low streamflow and modified hydraulic conditions.

2. Thermal infrared radiation (TIR) surveys and instream temperature data indicate that Wenatchee River, Icicle Creek, and Nason Creek experience a downstream heating pattern (Figure 20). This tendency is more noticeable in the lower reaches of the Wenatchee River where riparian vegetation and precipitation are scarce. The river is more exposed to direct solar radiation over a larger air-water interface as the river widens towards its confluence with the Columbia River.

3. In addition to load allocations for effective shade in the study area, the following management activities are recommended for implementation to attain temperatures that comply with the water quality standards provision for natural conditions:

   - For U.S. Forest Service land, the riparian reserves in the Northwest Forest Plan are recommended for establishment of mature riparian vegetation.

   - For privately owned forest land, the riparian vegetation prescriptions in the Forest and Fish Report are recommended for all perennial streams. Load allocations are included in this TMDL for forest lands in accordance with the section of the Forest and Fish Report entitled, *TMDLs produced prior to 2009 in mixed use watersheds*.

   - For areas that are not managed in accordance with either the Northwest Forest Plan or the Forest and Fish Report, such as private non-forest areas, voluntary programs to increase riparian vegetation should be developed (e.g., riparian buffers or conservation easements sponsored under the U.S. Department of Agriculture Natural Resources Conservation Service's Conservation Reserve Enhancement Program).

   - Instream flows and water withdrawals are managed through regulatory avenues separate from TMDLs. However, stream temperature is related to the amount of instream flow, and increases in flow generally result in decreases in maximum temperatures. Future projects that have the potential to increase groundwater inflows to streams in the watershed should be encouraged. Voluntary retirement or purchase of existing water rights for conservation to instream flow also should be encouraged.

   - Management activities should control potential channel widening processes. Reductions in channel width are expected as mature riparian vegetation is established. Management activities that would reduce the loading of sediment to the surface waters from upland and channel erosion also are recommended.

- Hyporheic exchange flows and groundwater discharges are important to maintain the current temperature regime and reduce maximum daily instream temperatures. Factors that influence hyporheic exchange flow include the vertical hydraulic gradient between surface and subsurface waters as well as the hydraulic conductivity of streambed sediments. Activities that reduce the hydraulic conductivity of streambed sediments could increase stream temperatures. Management activities should reduce upland and channel erosion and avoid sedimentation of fine materials in the stream substrate.

4. To determine the effects of management strategies within the Wenatchee River basin, regular monitoring is recommended. Continuously-recording water temperature monitors should be deployed from July through August to capture the critical conditions. It is suggested that a minimal sampling program include sampling near the mouths of the following waterbodies: Wenatchee River, Icicle Creek, Nason Creek, Peshastin Creek, and Mission Creek.

5. Shade management practices involve the development of mature riparian vegetation, which requires many years to become established. Figure 27 can be used to prioritize reaches that need riparian restoration efforts. Data on spawning area locations can be compared to the shade deficit map to further prioritize reaches that need riparian restoration. Also, TIR images can be useful for describing spatial distribution patterns of water temperature in the surveyed streams. The TIR and visible band images are effective tools to map coldwater refugia for fish and to detect regions that can be improved for fish survival.

6. Interim monitoring of water temperatures during the summer is recommended, perhaps at five-year intervals. Interim monitoring of the composition and extent of riparian vegetation also is recommended (e.g., by using photogrammetry or remote sensing methods, hemispherical photography, angular canopy densiometers, or solar pathfinder instruments).

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Appendices

Appendix A

Use designations for the revised WAC 173-201a for WRIA 45 (Wenatchee)

2003 Revised WAC 173-201a, Table 602, WRIA 45 (Wenatchee)	Aquatic Life Uses						Recreational Uses			Water Supply Uses				Misc. Uses				
Use Designations for Fresh Waters by Water Resource Inventory Area (WRIA)	Char	Core Salmon/Trout	Non-Core Salmon/Trout	Salmon/Trout Rearing	Redband Trout	Warm Water Species	Ex Primary Cont	Primary Cont	Secondary Cont	Domestic Water	Industrial Water	Agricultural Water	Stock Water	Wildlife Habitat	Harvesting	Commerce/Navigation	Boating	Aesthetics
Chikamin Creek and all tributaries.	✓						✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Chiwaukum Creek and South Fork Chiwaukum Creek: All waters (including tributaries) above the junction.	✓						✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Chiwawa River from mouth to unnamed creek at longitude -120.8409 and latitude 48.0595 (near Phelps Creek).		✓					✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Chiwawa River and all tributaries above unnamed creek at longitude -120.8409 and latitude 48.0595 (near Phelps Creek).	✓						✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Dry Creek and Chumstick Creek: All waters (including tributaries) above the junction, except those waters in or above the Wenatchee National Forest.	✓							✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Dry Creek and Chumstick Creek: All waters (including tributaries) above the junction that are in or above the Wenatchee National Forest.	✓						✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Eagle Creek and the unnamed tributary at longitude -120.5165 and latitude 47.6544: All waters (including tributaries) above the junction, except those waters in or above the Wenatchee National Forest.	✓							✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Eagle Creek and the unnamed tributary at longitude -120.5165 and latitude 47.6544: All waters (including tributaries) above the junction that are in or above the Wenatchee National Forest.	✓						✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Icicle Creek and all tributaries above unnamed creek at longitude -120.9547 and latitude 47.6206 (near French Creek).	✓						✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Little Giant Creek and all tributaries.	✓						✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Rock Creek and all tributaries.	✓						✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Second Creek and the unnamed tributary at longitude -120.5935 and latitude 47.7384: All waters (including tributaries) above the junction.	✓						✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Van Creek and the unnamed tributary at longitude -120.5373 and latitude 47.6722: All waters (including tributaries) above the junction.	✓						✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Wenatchee River from Wenatchee National Forest boundary (river mile 27.1) to Chiwawa River.		✓					✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Wenatchee River and all tributaries upstream of Chiwawa River.	✓						✓			✓	✓	✓	✓	✓	✓	✓	✓	✓

Appendix B

Load allocations for effective shade for the Wenatchee River, Icicle Creek, and Nason Creek

Table B1. Load allocations for effective shade in the Wenatchee River for the condition of mature riparian vegetation.

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for daily average shortwave solar radiation on August 1 (W/m^2)	Load allocation for effective shade on August 1 (percent)
86.5	86	300	4%
86	85.5	276	11%
85.5	85	282	9%
85	84.5	276	11%
84.5	84	283	9%
84	83.5	278	11%
83.5	83	274	12%
83	82.5	280	10%
82.5	82	250	19%
82	81.5	264	15%
81.5	81	271	13%
81	80.5	280	10%
80.5	80	285	8%
80	79.5	289	7%
79.5	79	257	17%
79	78.5	280	10%
78.5	78	289	7%
78	77.5	266	14%
77.5	77	269	13%
77	76.5	260	16%
76.5	76	274	12%
76	75.5	270	13%
75.5	75	270	13%
75	74.5	280	10%
74.5	74	276	11%
74	73.5	246	21%
73.5	73	270	13%
73	72.5	261	16%
72.5	72	265	15%
72	71.5	278	10%
71.5	71	269	13%
71	70.5	273	12%
70.5	70	258	17%
70	69.5	279	10%
69.5	69	279	10%
69	68.5	276	11%
68.5	68	286	8%
68	67.5	282	9%
67.5	67	270	13%
67	66.5	296	4%
66.5	66	275	11%
66	65.5	286	8%
65.5	65	292	6%

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for daily average shortwave solar radiation on August 1 (W/m^2)	Load allocation for effective shade on August 1 (percent)
65	64.5	292	6%
64.5	64	298	4%
64	63.5	285	8%
63.5	63	298	4%
63	62.5	284	8%
62.5	62	300	3%
62	61.5	280	10%
61.5	61	264	15%
61	60.5	253	18%
60.5	60	272	12%
60	59.5	251	19%
59.5	59	295	5%
59	58.5	280	10%
58.5	58	255	18%
58	57.5	271	12%
57.5	57	228	26%
57	56.5	273	12%
56.5	56	214	31%
56	55.5	233	25%
55.5	55	241	22%
55	54.5	248	20%
54.5	54	229	26%
54	53.5	237	23%
53.5	53	257	17%
53	52.5	213	31%
52.5	52	213	31%
52	51.5	224	28%
51.5	51	202	35%
51	50.5	225	27%
50.5	50	253	18%
50	49.5	243	21%
49.5	49	246	20%
49	48.5	222	28%
48.5	48	241	22%
48	47.5	232	25%
47.5	47	180	42%
47	46.5	223	28%
46.5	46	180	42%
46	45.5	233	24%
45.5	45	256	17%
45	44.5	211	32%
44.5	44	253	18%
44	43.5	249	19%
43.5	43	253	18%
43	42.5	227	26%

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for daily average shortwave solar radiation on August 1 (W/m^2)	Load allocation for effective shade on August 1 (percent)
42.5	42	245	20%
42	41.5	242	21%
41.5	41	285	7%
41	40.5	280	9%
40.5	40	291	5%
40	39.5	292	5%
39.5	39	291	5%
39	38.5	295	4%
38.5	38	288	6%
38	37.5	277	10%
37.5	37	280	9%
37	36.5	288	6%
36.5	36	276	10%
36	35.5	283	8%
35.5	35	293	5%
35	34.5	282	8%
34.5	34	282	8%
34	33.5	288	6%
33.5	33	292	5%
33	32.5	283	8%
32.5	32	288	6%
32	31.5	286	7%
31.5	31	289	6%
31	30.5	294	4%
30.5	30	288	6%
30	29.5	289	6%
29.5	29	279	9%
29	28.5	278	9%
28.5	28	282	8%
28	27.5	271	12%
27.5	27	287	6%
27	26.5	280	9%
26.5	26	287	7%
26	25.5	291	5%
25.5	25	291	5%
25	24.5	287	7%
24.5	24	298	3%
24	23.5	284	8%
23.5	23	291	5%
23	22.5	284	7%
22.5	22	293	4%
22	21.5	293	4%
21.5	21	292	5%
21	20.5	294	4%
20.5	20	295	4%

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for daily average shortwave solar radiation on August 1 (W/m^2)	Load allocation for effective shade on August 1 (percent)
20	19.5	295	4%
19.5	19	295	4%
19	18.5	288	6%
18.5	18	292	5%
18	17.5	293	4%
17.5	17	288	6%
17	16.5	280	9%
16.5	16	293	5%
16	15.5	298	3%
15.5	15	296	3%
15	14.5	297	3%
14.5	14	293	4%
14	13.5	290	5%
13.5	13	282	8%
13	12.5	289	6%
12.5	12	280	8%
12	11.5	287	6%
11.5	11	287	6%
11	10.5	295	4%
10.5	10	281	8%
10	9.5	280	9%
9.5	9	285	7%
9	8.5	295	3%
8.5	8	291	5%
8	7.5	293	4%
7.5	7	297	3%
7	6.5	300	2%
6.5	6	299	2%
6	5.5	299	2%
5.5	5	295	3%
5	4.5	296	3%
4.5	4	295	4%
4	3.5	295	4%
3.5	3	295	4%
3	2.5	296	3%
2.5	2	290	5%
2	1.5	288	6%
1.5	1	289	6%
1	0.5	298	2%
0.5	0	300	2%

Table B2. Load allocations for effective shade in Icicle Creek for the condition of mature riparian vegetation.

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for daily average shortwave solar radiation on August 1 (W/m^2)	Load allocation for effective shade on August 1 (percent)
30.1	29.6	102	67%
29.6	29.1	191	39%
29.1	28.6	175	44%
28.6	28.1	218	30%
28.1	27.6	222	29%
27.6	27.1	126	60%
27.1	26.6	197	37%
26.6	26.1	214	32%
26.1	25.6	219	30%
25.6	25.1	239	24%
25.1	24.6	226	28%
24.6	24.1	241	23%
24.1	23.6	258	18%
23.6	23.1	158	49%
23.1	22.6	181	42%
22.6	22.1	214	32%
22.1	21.6	187	40%
21.6	21.1	178	43%
21.1	20.6	142	55%
20.6	20.1	115	63%
20.1	19.6	138	56%
19.6	19.1	114	64%
19.1	18.6	124	60%
18.6	18.1	120	62%
18.1	17.6	156	50%
17.6	17.1	136	57%
17.1	16.6	215	31%
16.6	16.1	162	48%
16.1	15.6	191	39%
15.6	15.1	174	44%
15.1	14.6	146	53%
14.6	14.1	268	14%
14.1	13.6	177	43%
13.6	13.1	189	39%
13.1	12.6	253	19%
12.6	12.1	215	31%
12.1	11.6	177	43%
11.6	11.1	173	44%
11.1	10.6	123	60%
10.6	10.1	182	41%
10.1	9.6	177	43%
9.6	9.1	183	41%
9.1	8.6	198	36%

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for daily average shortwave solar radiation on August 1 (W/m^2)	Load allocation for effective shade on August 1 (percent)
8.6	8.1	225	27%
8.1	7.6	173	44%
7.6	7.1	230	25%
7.1	6.6	195	37%
6.6	6.1	87	72%
6.1	5.6	86	72%
5.6	5.1	136	56%
5.1	4.6	234	24%
4.6	4.1	206	33%
4.1	3.6	172	44%
3.6	3.1	209	32%
3.1	2.6	227	26%
2.6	2.1	178	42%
2.1	1.6	196	36%
1.6	1.1	238	23%
1.1	0.6	211	31%
0.6	0	221	28%

Table B3. Load allocations for effective shade in the LNFH canal for the condition of mature riparian vegetation.

Distance from upstream end of canal to upstream segment boundary (Km)	Distance from upstream end of canal to downstream segment boundary (Km)	Load allocation for daily average shortwave solar radiation on August 1 (W/m^2)	Load allocation for effective shade on August 1 (percent)
0	100	254	18%
100	200	252	18%
200	300	237	23%
300	400	228	26%
400	500	225	27%
500	600	233	25%
600	700	226	27%
700	800	220	29%
800	900	228	26%
900	1000	226	27%
1000	1100	225	27%
1100	1200	222	28%
1200	1300	227	26%

LNFH = Leavenworth National Fish Hatchery

Table B4. Load allocations for effective shade in Nason Creek for the condition of mature riparian vegetation.

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for daily average shortwave solar radiation on August 1 (W/m^2)	Load allocation for effective shade on August 1 (percent)
41.9	41.4	28	91%
41.4	40.9	11	97%
40.9	40.4	21	93%
40.4	39.9	18	94%
39.9	39.4	30	90%
39.4	38.9	26	92%
38.9	38.4	67	79%
38.4	37.9	97	69%
37.9	37.4	84	73%
37.4	36.9	76	76%
36.9	36.4	71	77%
36.4	35.9	85	73%
35.9	35.4	57	82%
35.4	34.9	156	50%
34.9	34.4	107	66%
34.4	33.9	123	61%
33.9	33.4	82	74%
33.4	32.9	49	84%
32.9	32.4	53	83%
32.4	31.9	54	83%
31.9	31.4	80	74%
31.4	30.9	101	68%
30.9	30.4	115	63%
30.4	29.9	107	66%
29.9	29.4	95	70%
29.4	28.9	156	50%
28.9	28.4	132	58%
28.4	27.9	37	88%
27.9	27.4	42	87%
27.4	26.9	41	87%
26.9	26.4	40	87%
26.4	25.9	89	72%
25.9	25.4	223	29%
25.4	24.9	201	36%
24.9	24.4	210	33%
24.4	23.9	129	59%
23.9	23.4	259	17%
23.4	22.9	253	19%
22.9	22.4	178	43%
22.4	21.9	91	71%
21.9	21.4	98	69%
21.4	20.9	105	66%
20.9	20.4	212	32%

Distance from mouth to upstream segment boundary (Km)	Distance from mouth to downstream segment boundary (Km)	Load allocation for daily average shortwave solar radiation on August 1 (W/m^2)	Load allocation for effective shade on August 1 (percent)
20.4	19.9	226	27%
19.9	19.4	179	43%
19.4	18.9	163	48%
18.9	18.4	162	48%
18.4	17.9	150	52%
17.9	17.4	205	34%
17.4	16.9	212	32%
16.9	16.4	200	36%
16.4	15.9	252	19%
15.9	15.4	180	42%
15.4	14.9	107	66%
14.9	14.4	171	45%
14.4	13.9	174	44%
13.9	13.4	142	54%
13.4	12.9	108	65%
12.9	12.4	161	48%
12.4	11.9	146	53%
11.9	11.4	131	58%
11.4	10.9	151	52%
10.9	10.4	173	45%
10.4	9.9	139	55%
9.9	9.4	182	42%
9.4	8.9	185	41%
8.9	8.4	186	40%
8.4	7.9	142	54%
7.9	7.4	171	45%
7.4	6.9	204	35%
6.9	6.4	179	42%
6.4	5.9	178	43%
5.9	5.4	163	48%
5.4	4.9	174	44%
4.9	4.4	179	42%
4.4	3.9	136	56%
3.9	3.4	124	60%
3.4	2.9	173	44%
2.9	2.4	128	59%
2.4	1.9	104	67%
1.9	1.4	165	47%
1.4	0.9	147	53%
0.9	0.4	142	54%
0.4	0	162	48%

Appendix C

Load allocations for effective shade for miscellaneous perennial streams in the Wenatchee River basin based on bankfull width and stream aspect

	Effective shade from vegetation (percent) at the stream center at various stream aspects (degrees from N)			Daily average global solar short-wave radiation (W/m2) at the stream center at various stream aspects (degrees from N)		
Bankfull width (m)	90 and 270 deg aspect	0 and 180 deg aspect	45, 135, 225 and 315 deg aspect	90 and 270 deg aspect	0 and 180 deg aspect	45, 135, 225 and 315 deg aspect
1	97.5%	96.6%	96.9%	8	11	10
2	97.4%	96.2%	96.6%	8	12	11
3	95.8%	92.6%	93.1%	13	23	22
4	94.3%	89.3%	90.0%	18	34	31
5	92.8%	86.8%	87.6%	22	42	39
6	91.0%	83.7%	84.0%	28	51	50
7	86.0%	79.7%	79.8%	44	64	63
8	80.1%	75.5%	76.0%	62	77	75
9	73.4%	71.6%	72.5%	84	89	86
10	66.8%	68.5%	69.3%	104	99	96
12	57.9%	62.5%	63.3%	132	118	115
14	50.3%	57.7%	58.2%	156	133	131
16	44.5%	53.6%	53.8%	174	145	145
18	40.0%	50.1%	49.9%	188	157	157
20	36.4%	46.9%	46.3%	200	167	168
25	29.8%	40.4%	38.9%	220	187	192
30	25.2%	35.3%	33.3%	235	203	209
35	21.9%	31.2%	29.0%	245	216	222
40	19.4%	27.8%	25.7%	253	226	233
45	17.4%	25.1%	23.0%	259	235	241
50	15.8%	22.8%	20.8%	264	242	248
55	14.4%	20.8%	19.0%	268	248	254
60	13.3%	19.2%	17.5%	272	253	259
65	12.3%	17.8%	16.1%	275	257	263
70	11.5%	16.6%	15.1%	277	261	266
75	10.8%	15.5%	14.0%	279	265	269
80	10.1%	14.5%	13.2%	281	268	272
85	9.5%	13.7%	12.4%	283	270	274
90	9.0%	12.9%	11.8%	285	272	276
95	8.6%	12.2%	11.2%	286	274	278
100	8.2%	11.6%	10.6%	287	276	280
110	7.4%	10.6%	9.7%	289	279	282
120	6.8%	9.7%	8.8%	291	282	284
130	6.3%	8.9%	8.2%	292	284	286
140	5.9%	8.3%	7.6%	293	286	288
150	5.5%	7.7%	7.1%	294	287	289
160	5.2%	7.2%	6.6%	295	288	290
170	4.9%	6.8%	6.2%	296	289	291
180	4.6%	6.4%	5.9%	296	290	292
190	4.3%	6.0%	5.6%	296	291	293
200	4.1%	5.7%	5.3%	297	292	293
210	3.9%	5.5%	5.1%	297	292	293
220	3.8%	5.2%	4.8%	297	292	294

	Effective shade from vegetation (percent) at the stream center at various stream aspects (degrees from N)			Daily average global solar short-wave radiation (W/m2) at the stream center at various stream aspects (degrees from N)		
Bankfull width (m)	90 and 270 deg aspect	0 and 180 deg aspect	45, 135, 225 and 315 deg aspect	90 and 270 deg aspect	0 and 180 deg aspect	45, 135, 225 and 315 deg aspect
230	3.6%	5.0%	4.6%	297	293	294
240	3.4%	4.8%	4.4%	298	293	295
250	3.3%	4.6%	4.2%	298	294	295
260	3.2%	4.4%	4.1%	298	295	296
270	3.1%	4.2%	3.9%	299	295	296
280	3.0%	4.1%	3.8%	299	295	296
300	2.8%	3.8%	3.5%	300	296	297